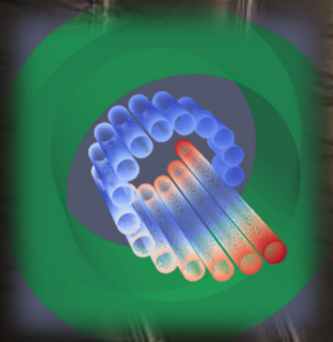
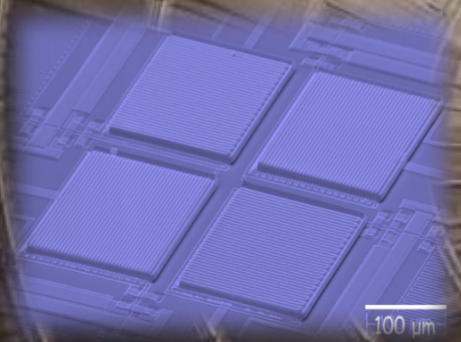
Direct Neutrino Mass Measurements

SnowMass workshop 2020



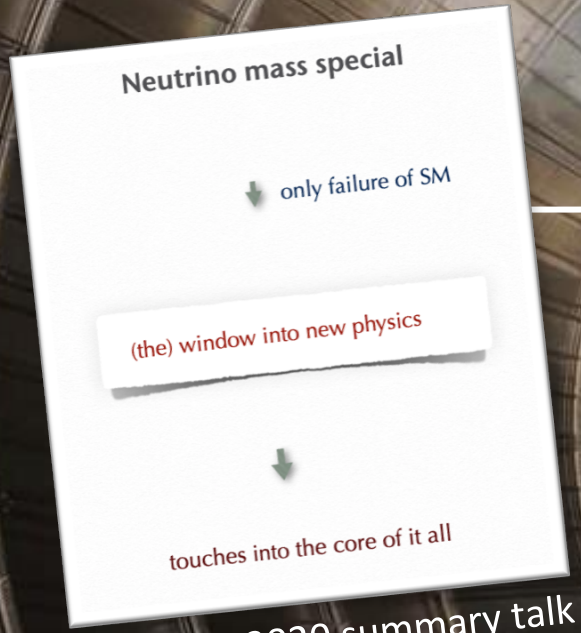


Prof. Dr. Susanne Mertens

Technical University Munich & Max Planck Institute for Physics

Direct Neutrino Mass Measurements

SnowMass workshop 2020



Neutrino-2020 summary talk
by Goran Senjanović

Prof. Dr. Susanne Mertens

Technical University Munich & Max Planck Institute for Physics

Neutrino mass

Cosmology

potential: m_ν = 10 - 50 meV

$$m_\nu = \sum_i m_i$$

Search for 0νßß

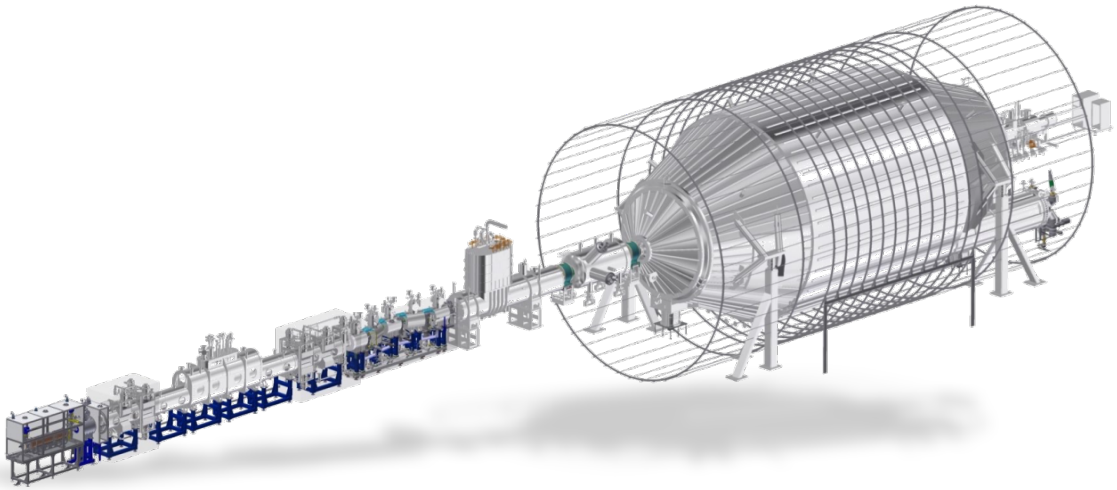
potential: $m_{ßß}$ = 7 - 17 meV

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

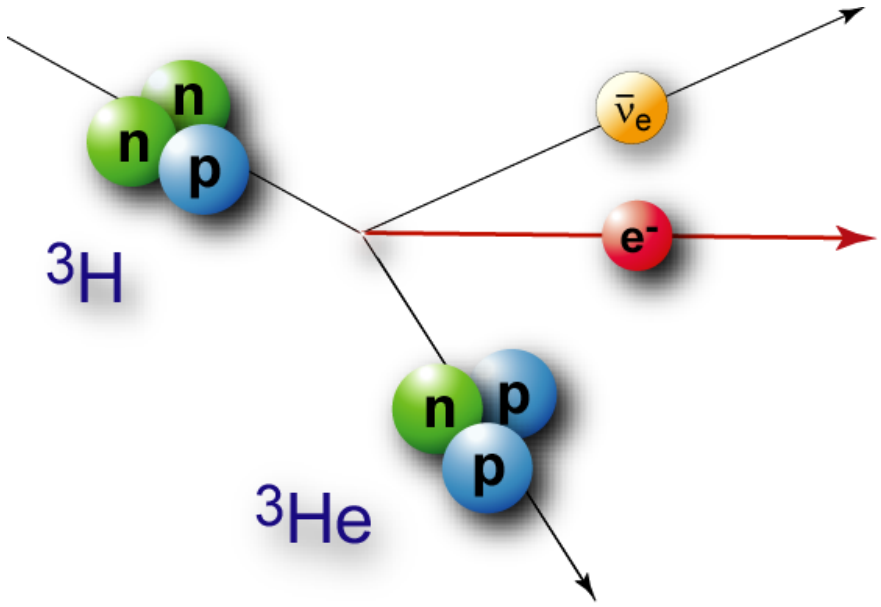
Kinematics of ß-decay

potential: m_β = 10 - 200 meV

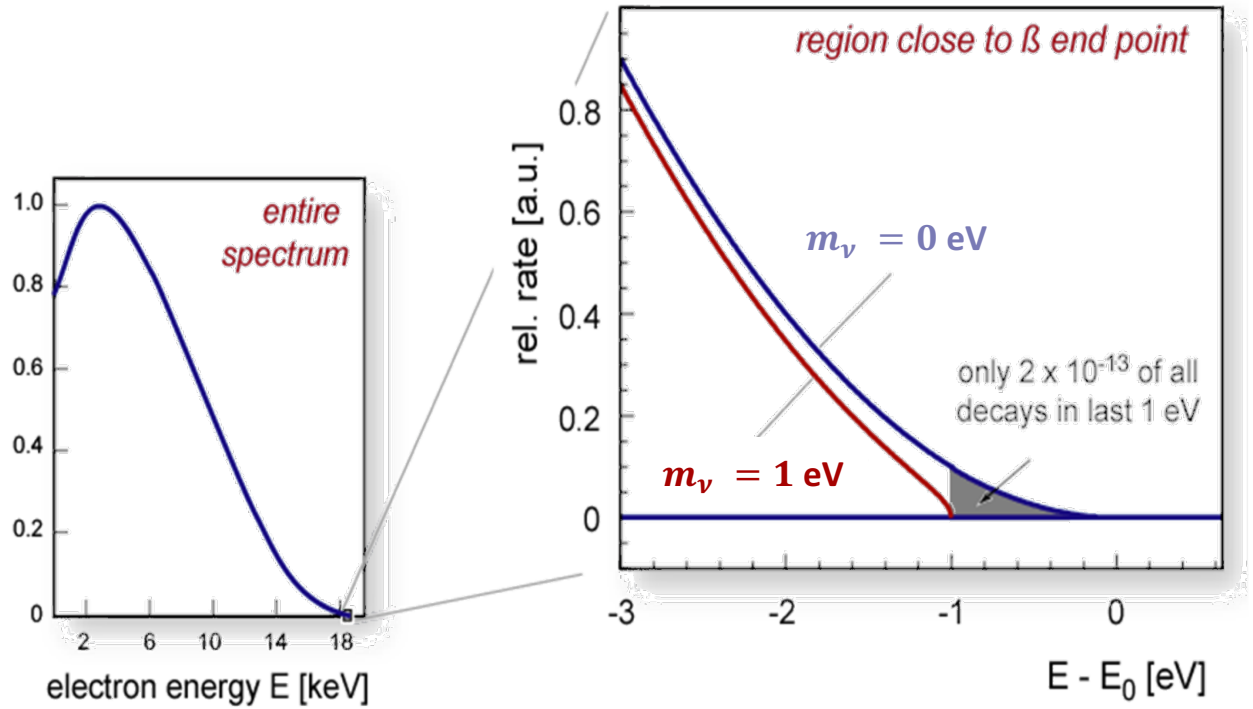
$$m_\beta^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$$



Direct neutrino mass measurement

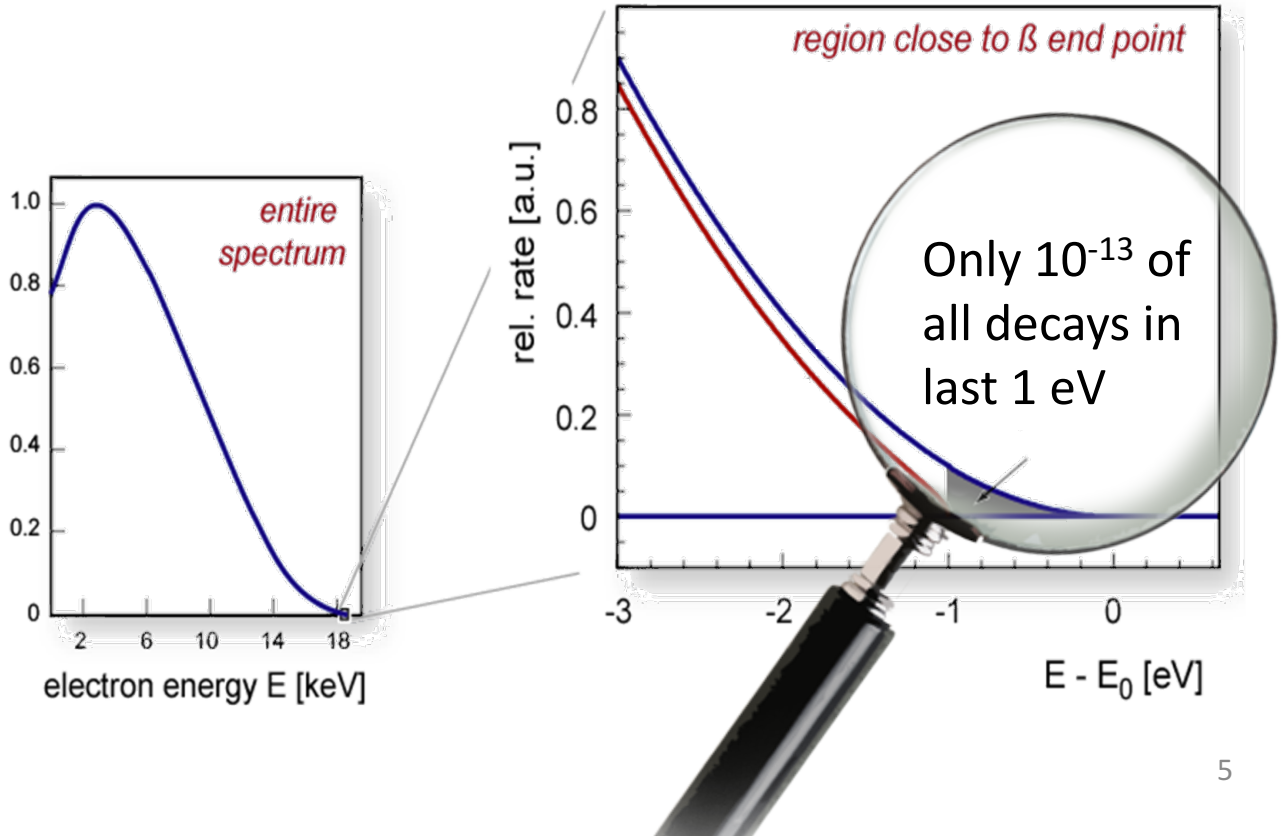


$$m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$$

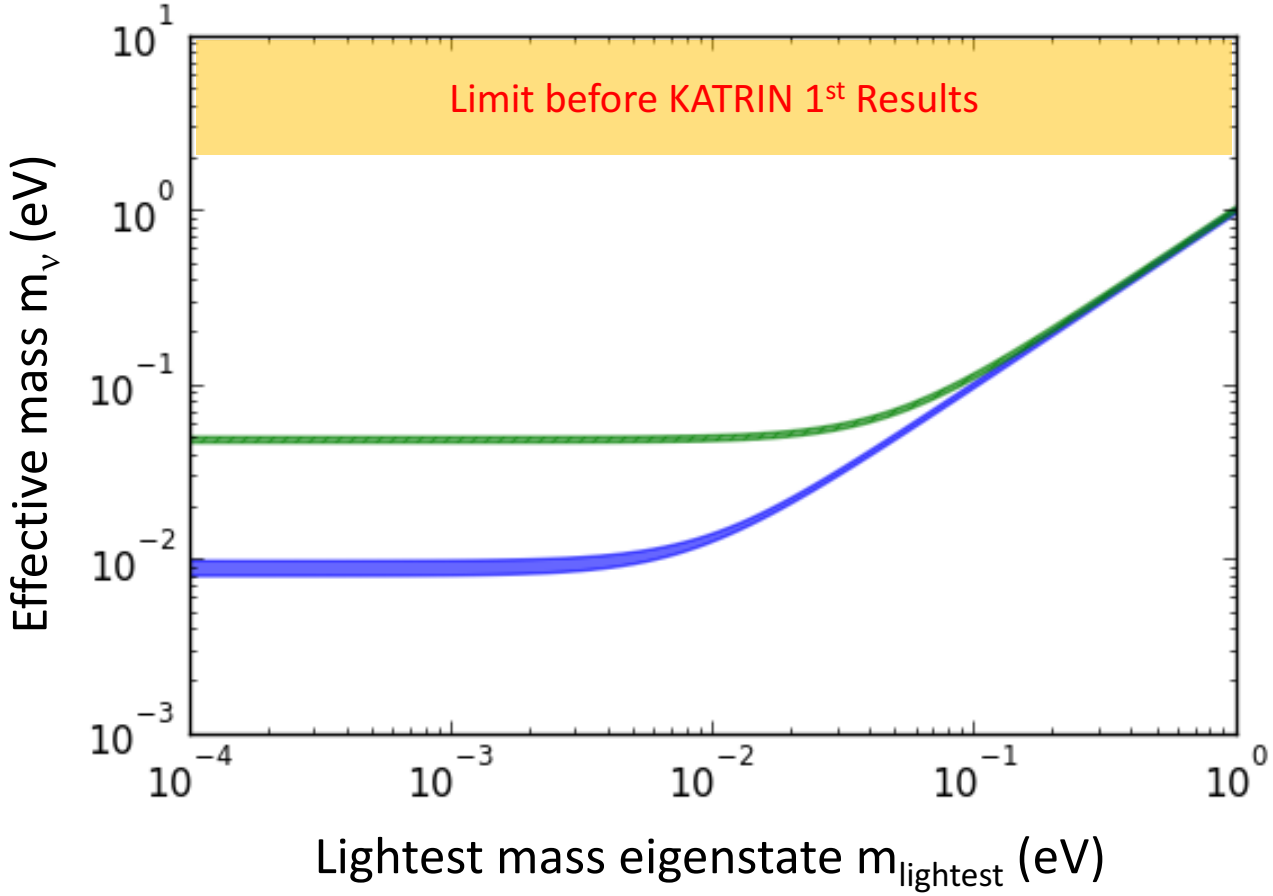


The challenge

- Ultra-strong β-source: 10^{11} decays/s
- Low background level < 0.1 cps
- Excellent energy resolution ~ 1 eV
- Precise understanding of spectrum



Where do we stand?



- Limit before KATRIN 1st Results: Mainz and Troitsk Experiment
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)

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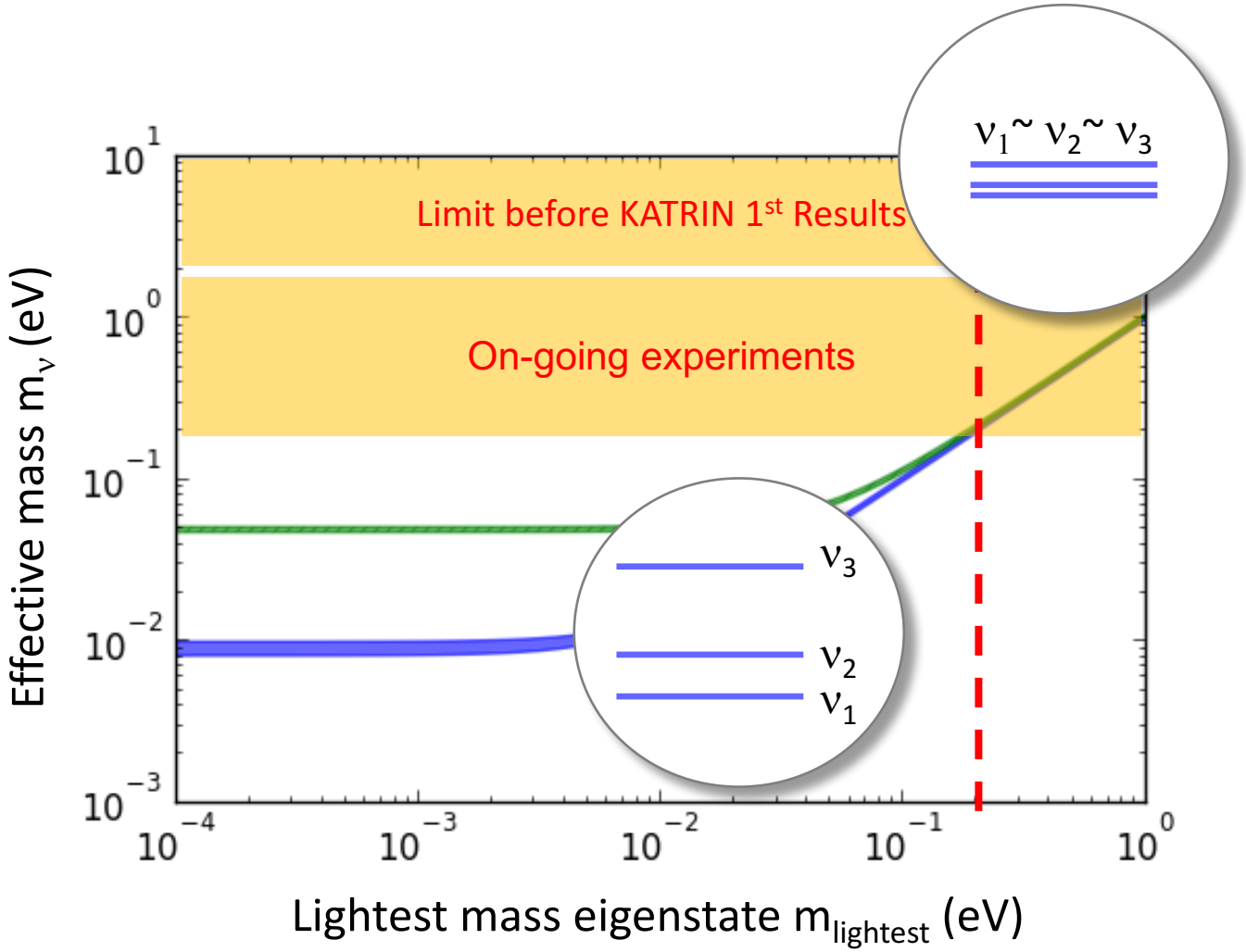

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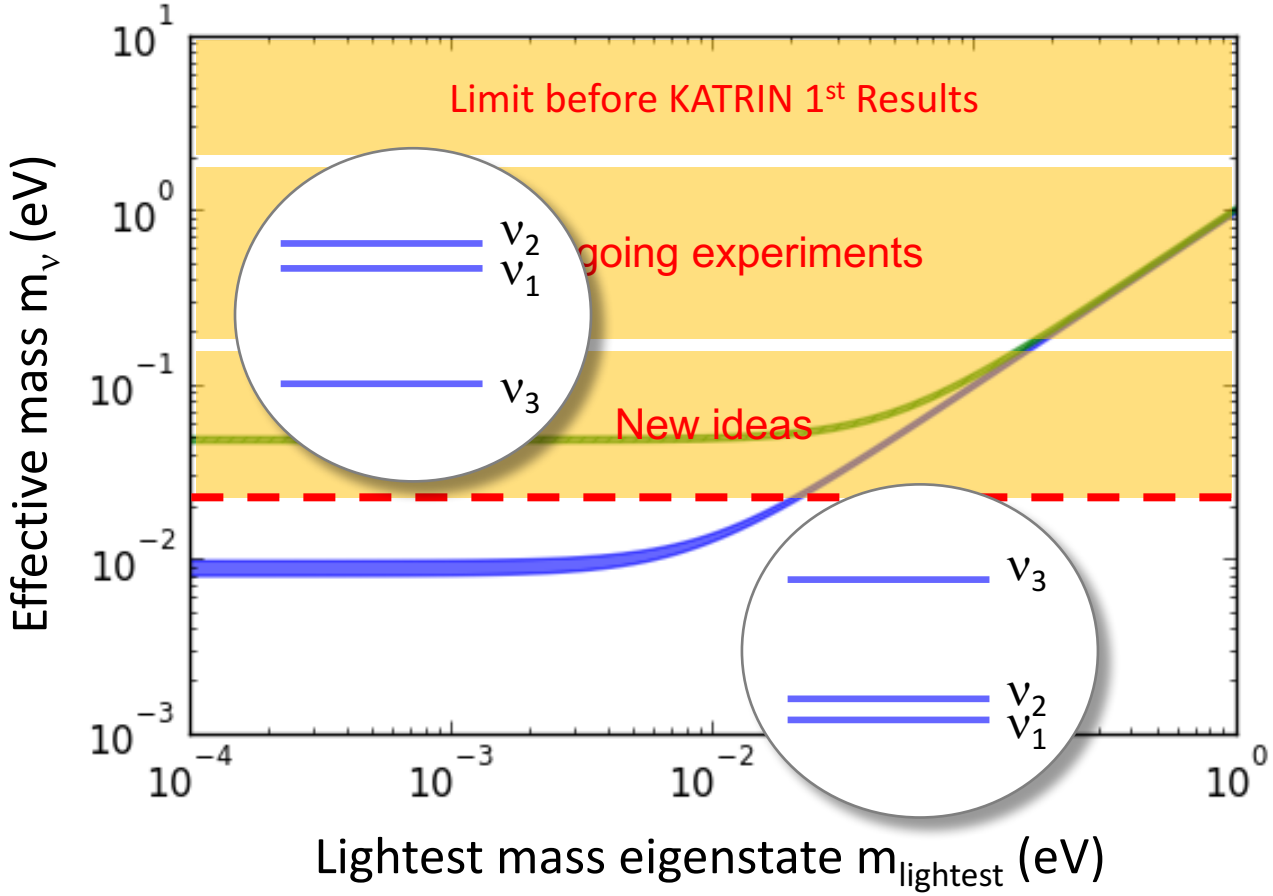
- Ongoing experiments: Distinguish between **degenerate** and **hierarchical** scenario

this talk

Where do we stand?



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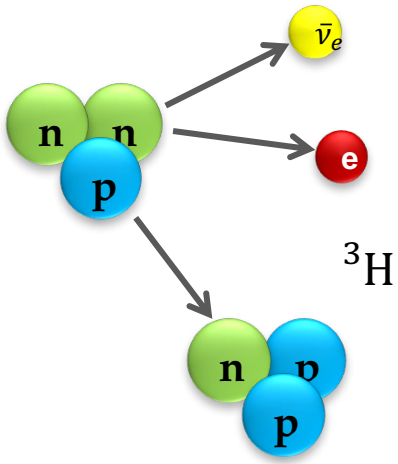
- Ongoing experiments: Distinguish between **degenerate** and **hierarchical** scenario

  this talk
- New ideas: Resolve **normal** vs **inverted** neutrino mass hierarchy

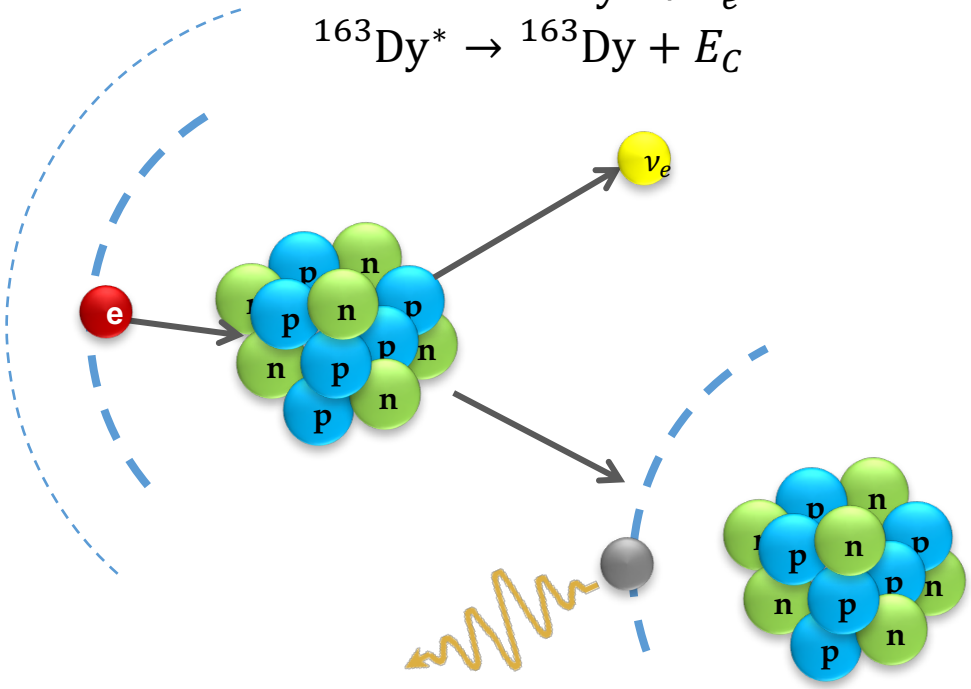
  following talks

Tritium and Holmium



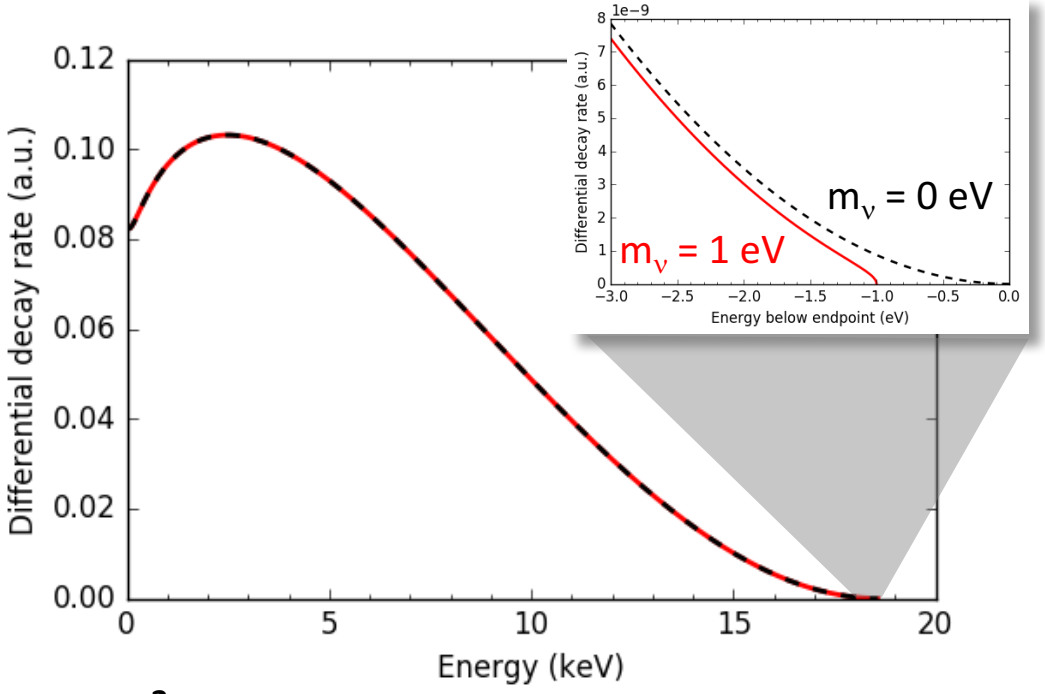
$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He}^{+} + e^{-} + \bar{\nu}_e$$

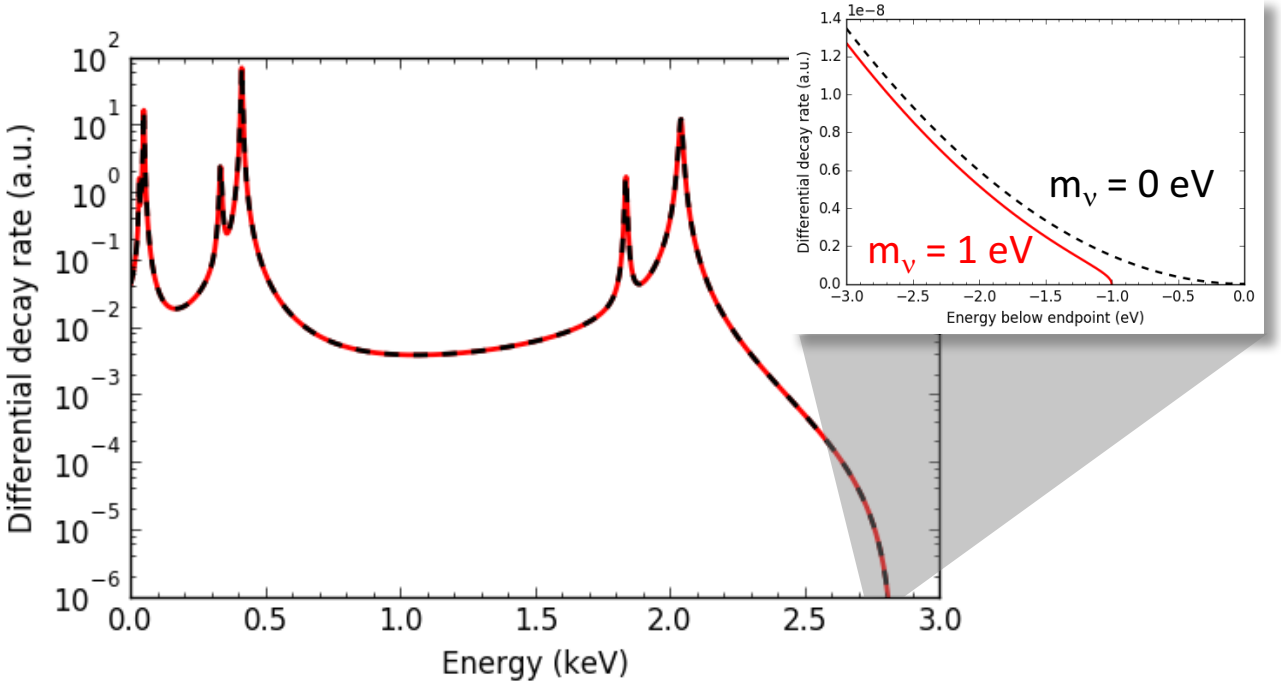
$$^{163}\mathrm{Ho} \rightarrow {}^{163}\mathrm{Dy}^{*} + \nu_e$$
$$^{163}\mathrm{Dy}^{*} \rightarrow {}^{163}\mathrm{Dy} + E_C$$



	^{3}H	^{163}Ho
	super-allowed β-decay	electron-capture decay
$T_{1/2}$	12.3 years	4500 years
E_0	18.6 keV	2.8 keV

Tritium and Holmium





	^{3}H	^{163}Ho
	super-allowed β-decay	electron-capture decay
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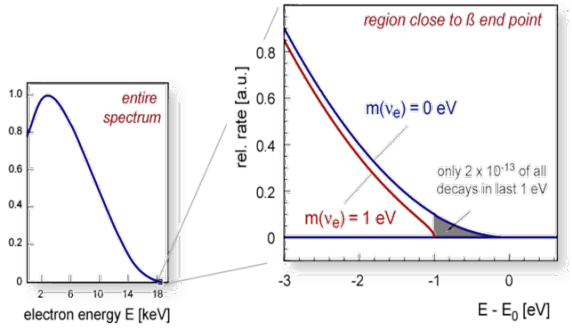
Experimental efforts

Electrostatic filter (MAC-E)

counting above threshold



frequency

Cyclotron Radiation

Phonons

heat

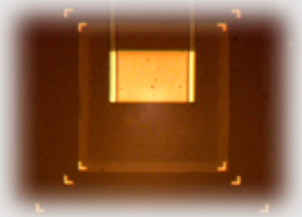
Experimental efforts

KATRIN
(Tritium)

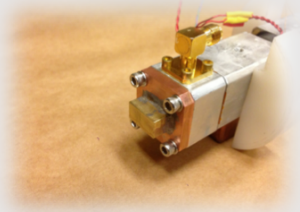
Electrostatic filter (MAC-E)

Ptolemy
(Tritium)

Holmes
(Holmium)



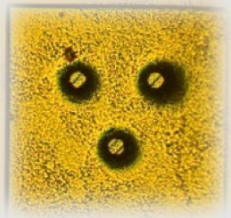
Project-8
(Tritium)



Cyclotron Radiation

Phonons

ECHo
(Holmium)



Experimental efforts

KATRIN
(Tritium)

Electrostatic filter (MAC-E)

Cyclotron Radiation

Phonons

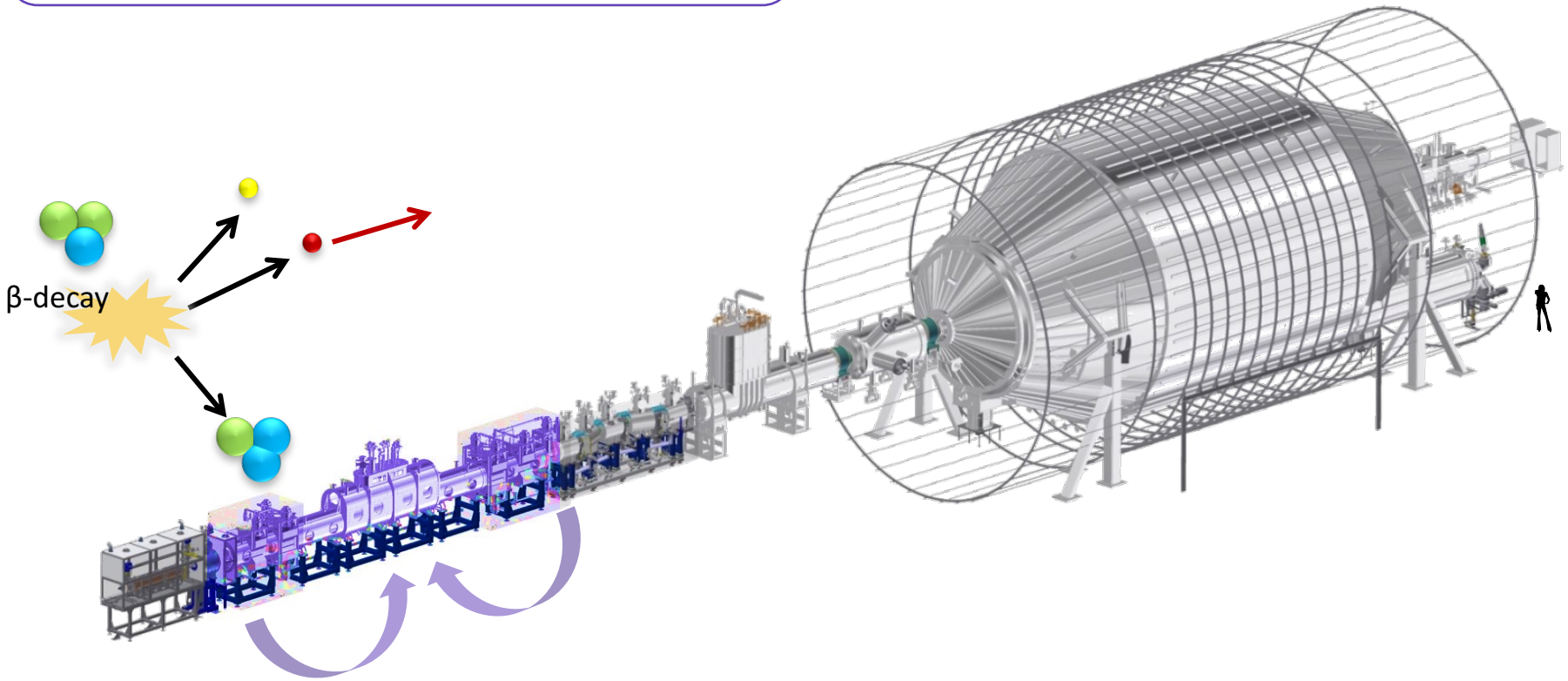
KATRIN

- **Experimental site: Karlsruhe Institute of Technology (KIT)**
- **International Collaboration (150 members)**
- **Design sensitivity: 0.2 eV (90% CL)**
  (1000 days of measurement time)

KATRIN Working Principle

Windowless gaseous tritium source

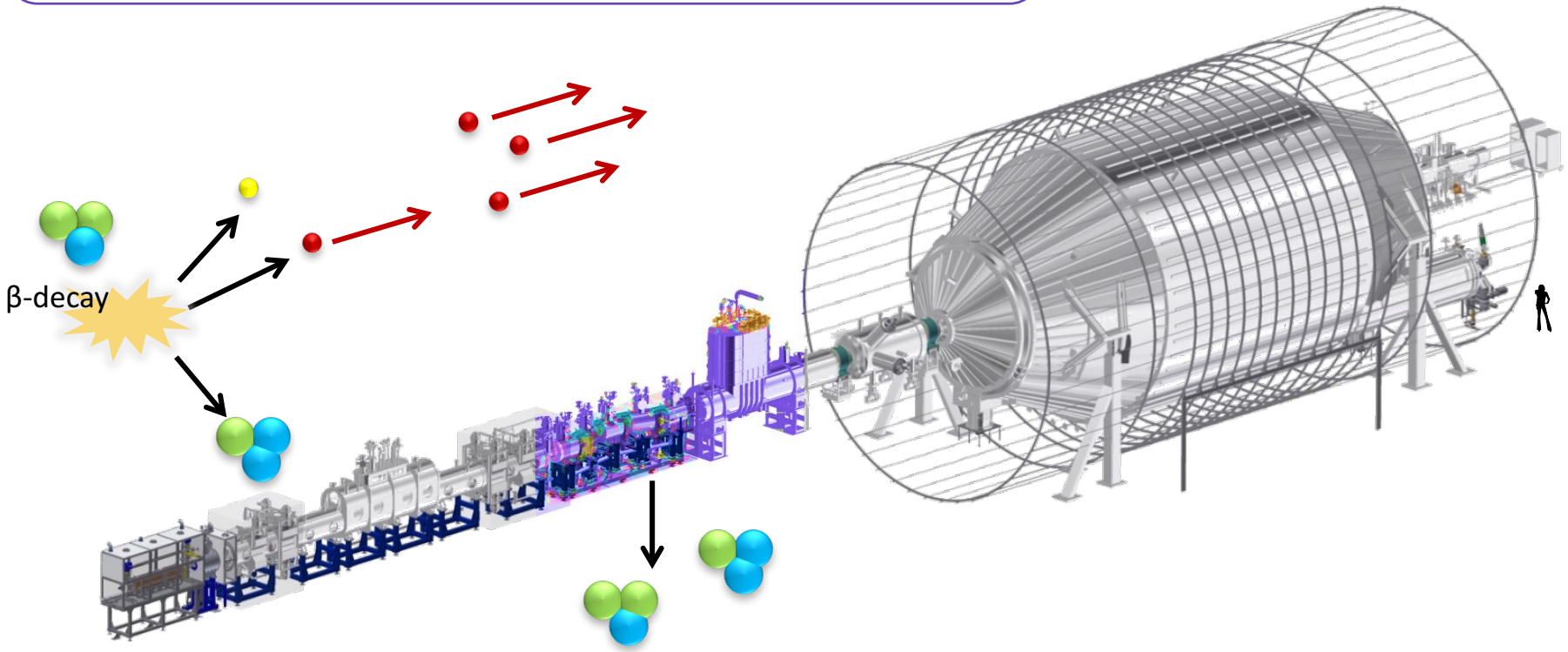
- molecular tritium in closed loop system
- 10^{11} decays/s



KATRIN Working Principle

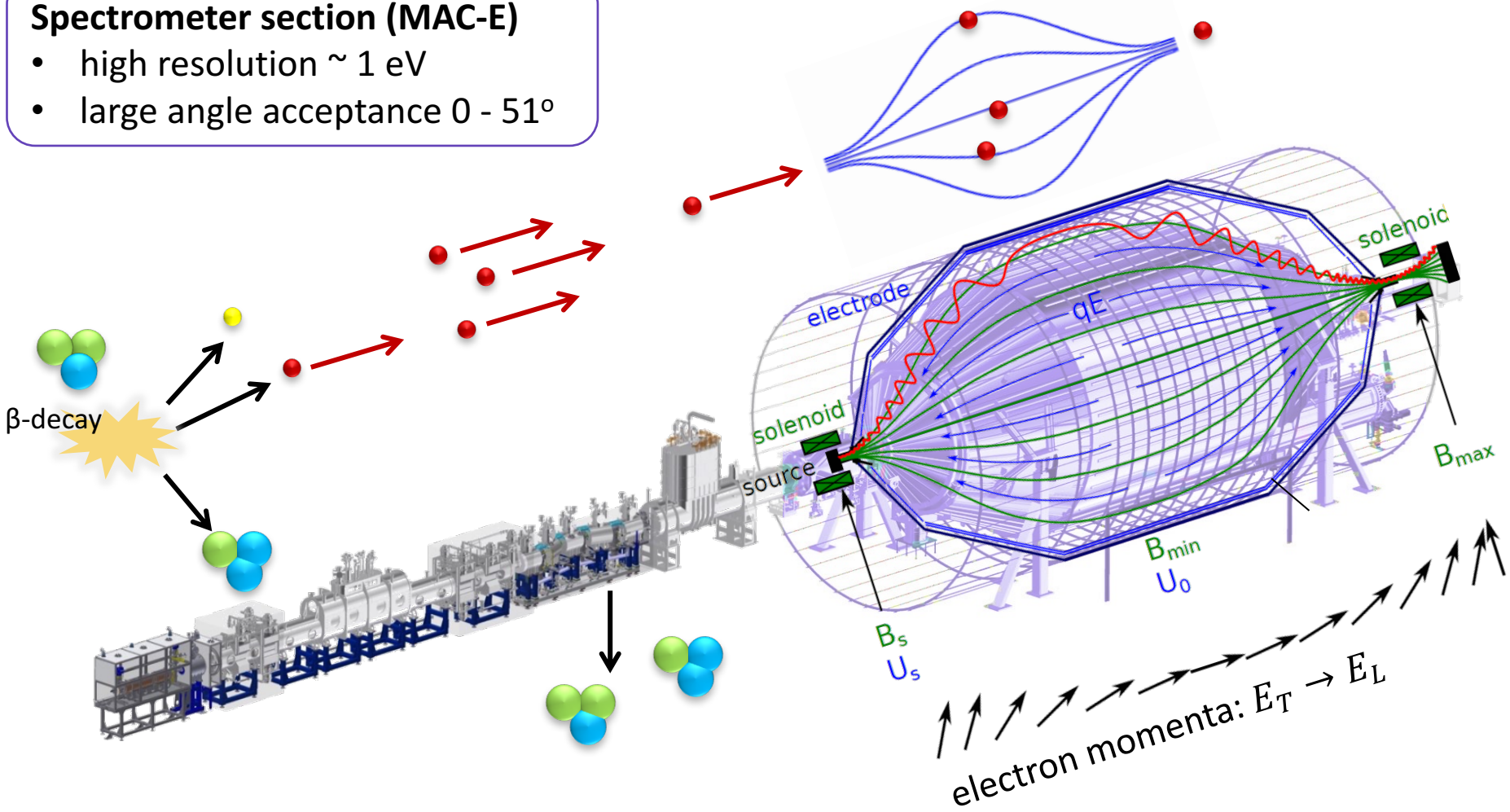
Transport section

- magnetic guidance of electrons (@ 4 T)
- tritium flow reduction by > 10^{14} + tritium ion removal



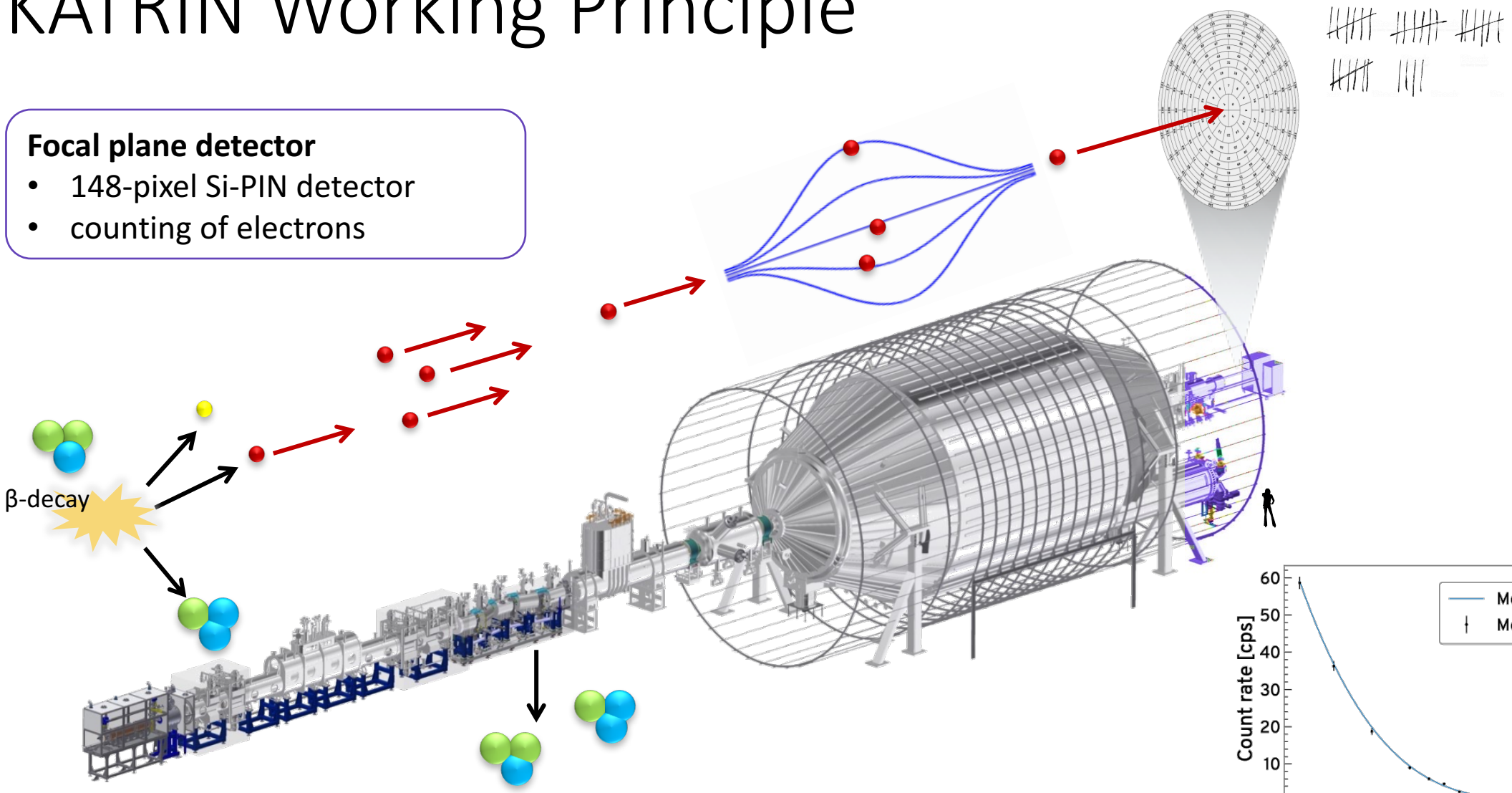
KATRIN Working Principle

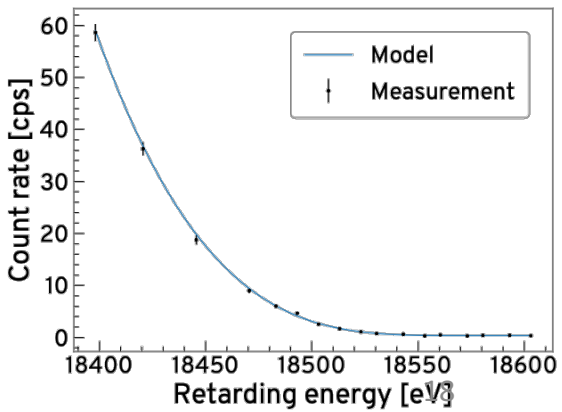
Spectrometer section (MAC-E)
- high resolution ~ 1 eV
- large angle acceptance 0 - 51°



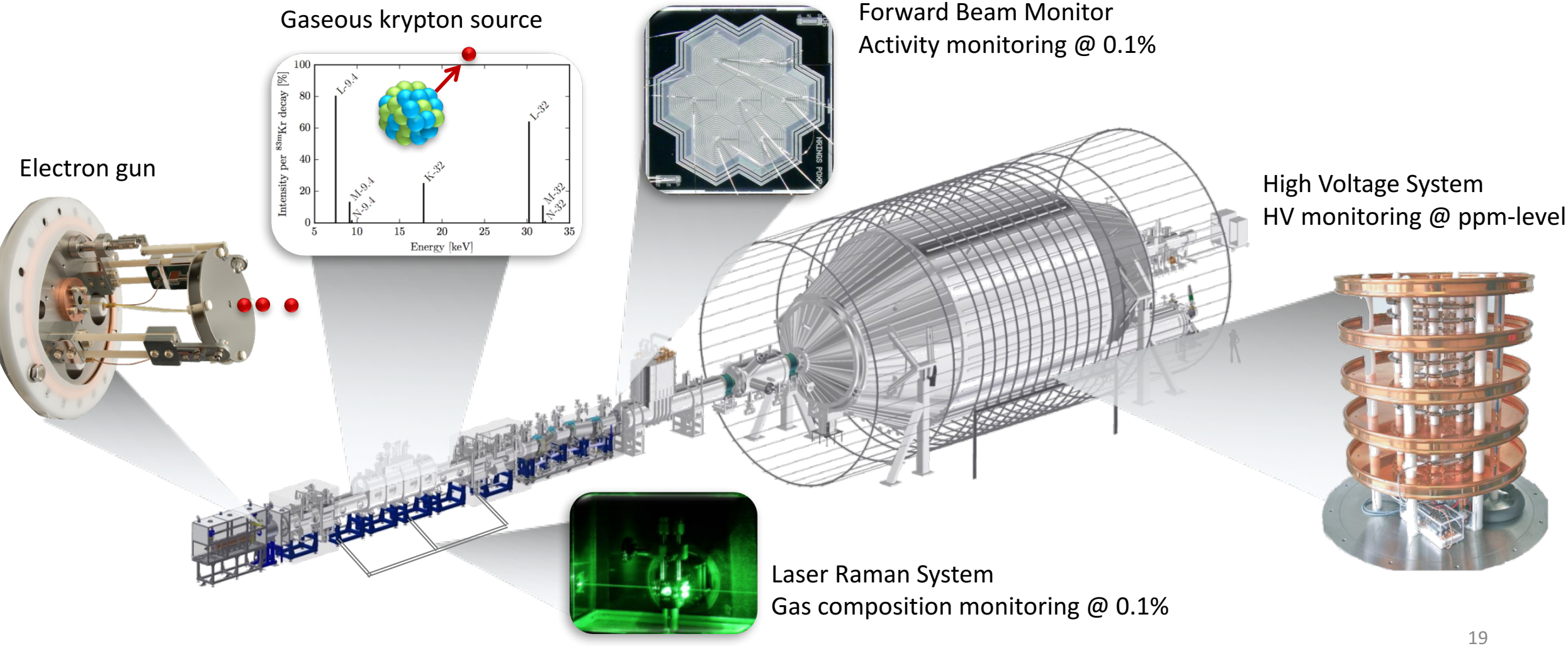
KATRIN Working Principle

Focal plane detector
- 148-pixel Si-PIN detector
- counting of electrons





KATRIN Working Principle



First neutrino mass campaign in 2019

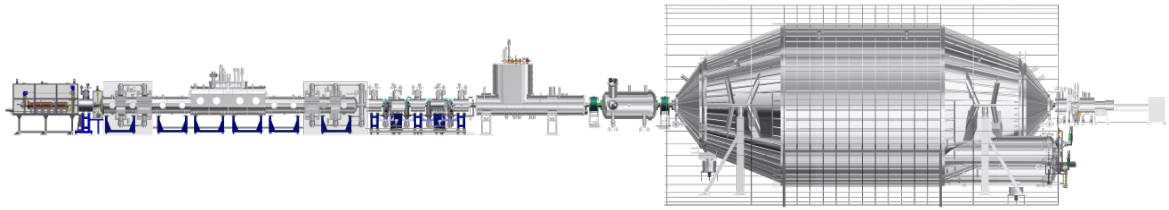
First ever high-activity tritium operation of KATRIN

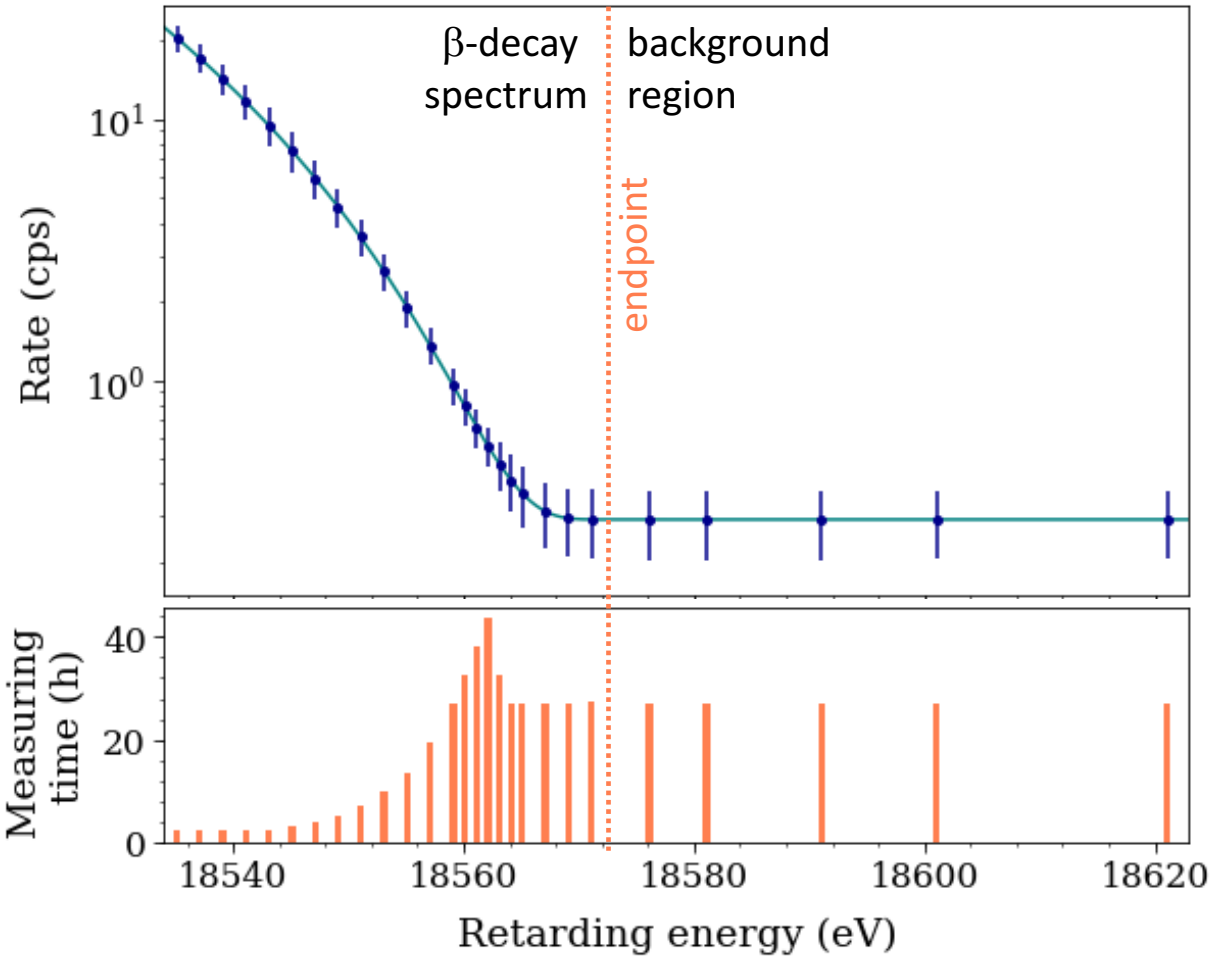
- Measurement time: **22 days**
- Gas density: **22%**
- Isotopic purity: **97.5% tritium**
- Source activity: **$2.45 \cdot 10^{10}$ Bq**
- Total statistics: **$2 \cdot 10^{6}$ e's**

Phys. Rev. Lett. 123, 221802

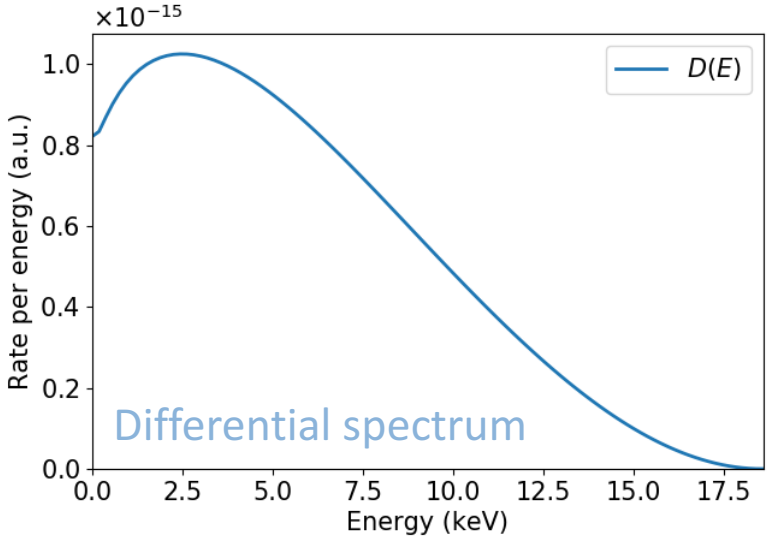
Measurement strategy

- # HV set points: **27**
- interval: **E_0 – 40 eV , E_0 + 50 eV**
- up/down scanning: **274 x 2 hours**
- HV stability: **20 mV (ppm-level)**

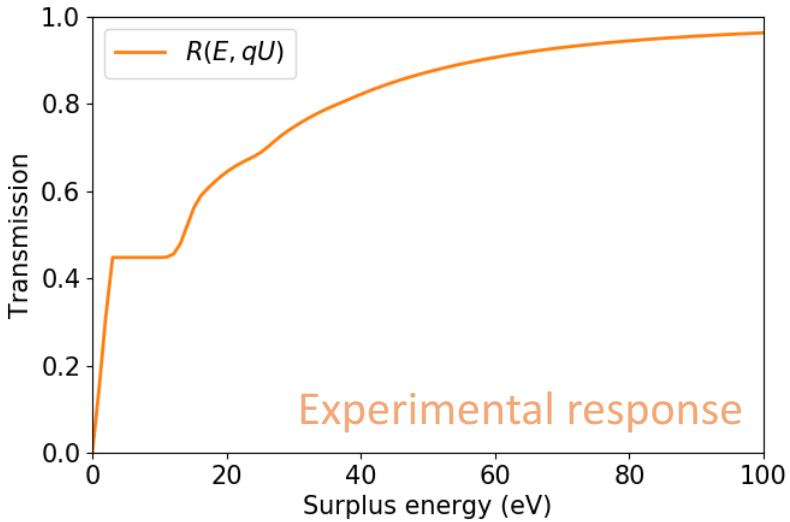




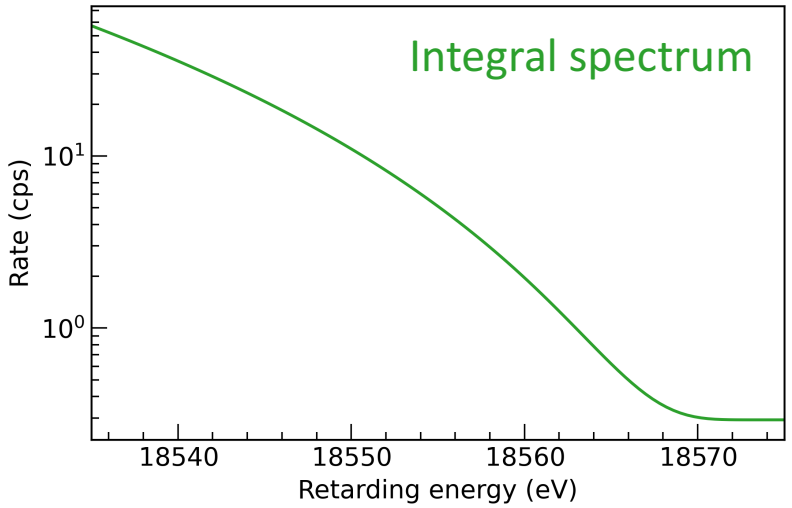
Tritium spectrum calculation



$$\Gamma(qU) \propto \boldsymbol{A} \cdot \int_{qU}^{\boldsymbol{E_0}} D\left(E; \boldsymbol{m_\nu^2}, \boldsymbol{E_0}\right) \cdot R(qU, E)\, dE + \boldsymbol{B}$$



- Molecular final states
- Doppler broadening
- Radiative corrections
- …



- Spectrometer resolution
- Scattering in the source
- Synchrotron radiation
- …

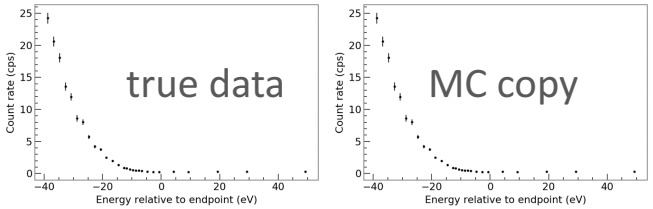
Y.-T. Lin et al, Phys. Rev. Lett. **124**, 222502 (2020)
A. Saenz et al, Phys. Rev. Lett. 84, 242 (2000) + updates

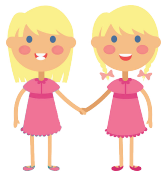
M. Kleesiek et al, EPC C, 79 (3) (2019)

Blinded analysis

Freeze analysis on MC-twin data

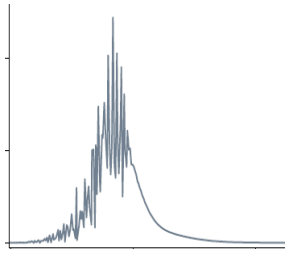
- MC-copy of each scan (with m_ν = 0 eV)

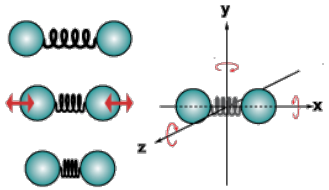




Blinded model

- Modified molecular final state dist.

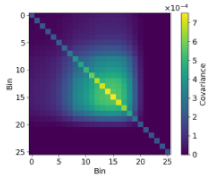


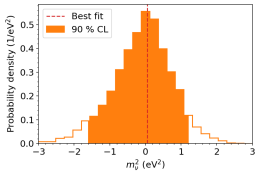


m_ν^2

Two independent analysis strategies

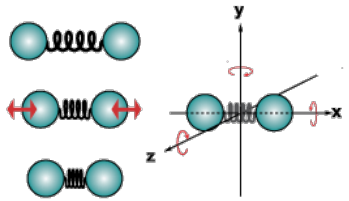
- Covariance matrix
- Monte Carlo propagation



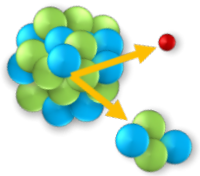


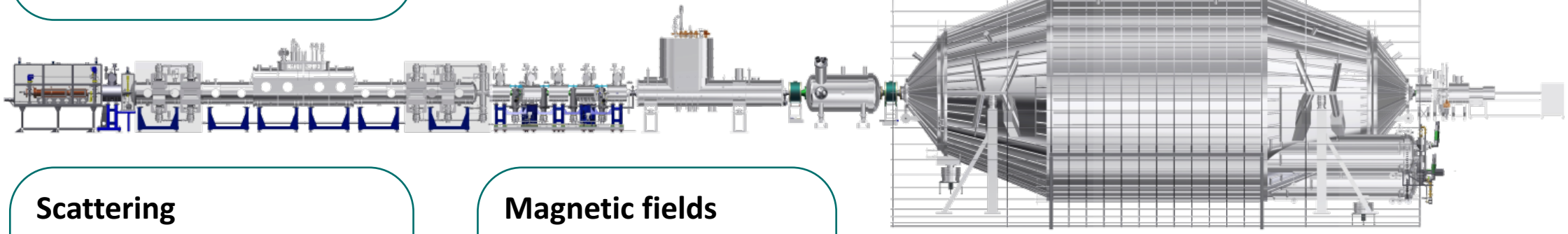
Systematic uncertainties

Molecular Final States

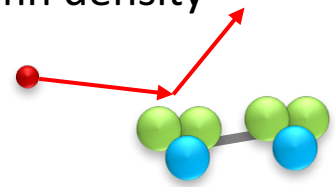


Background:
- time correlation
- retarding potential dependence





Scattering
- energy loss
- column density

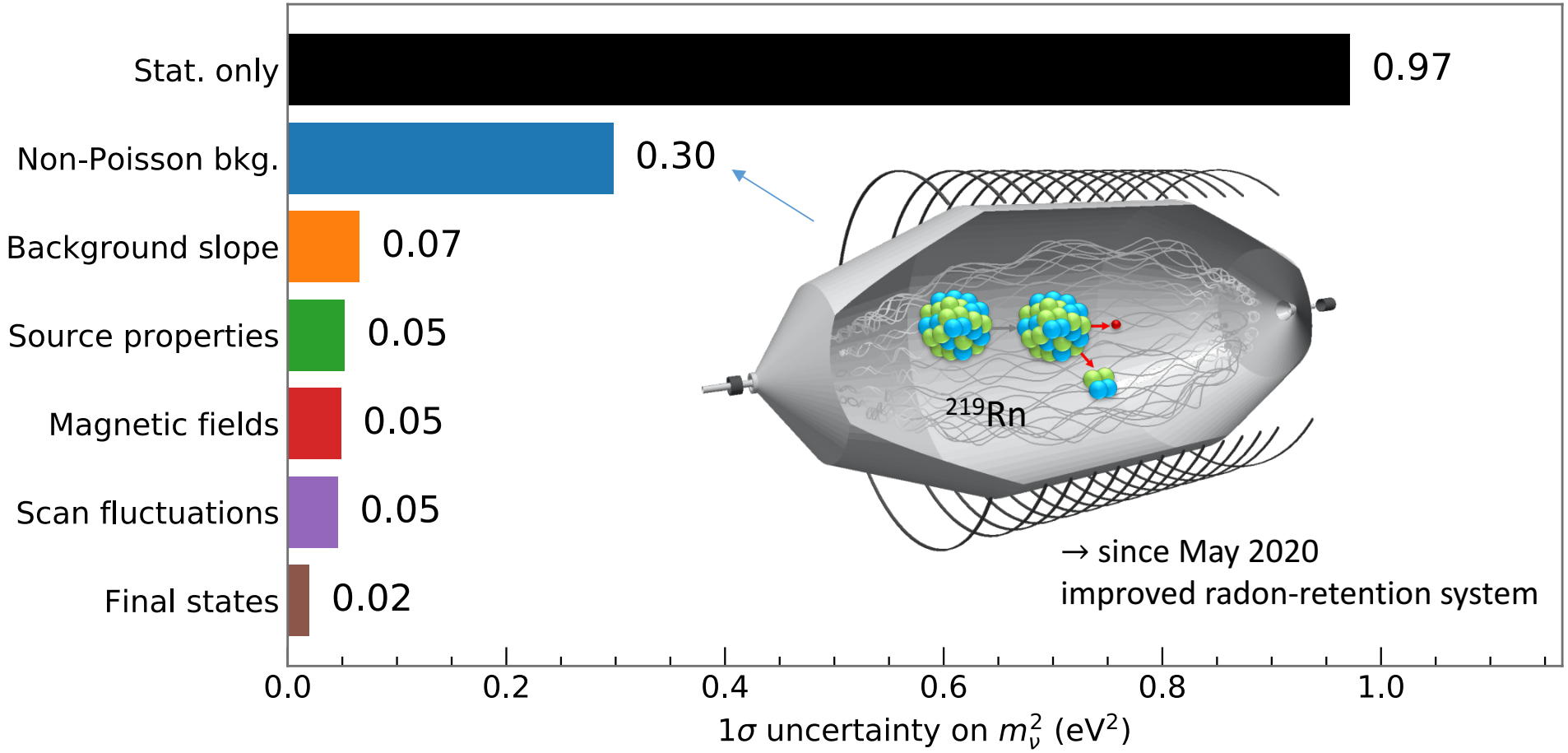


Magnetic fields
- source
- spectrometer
- detector

Data combination

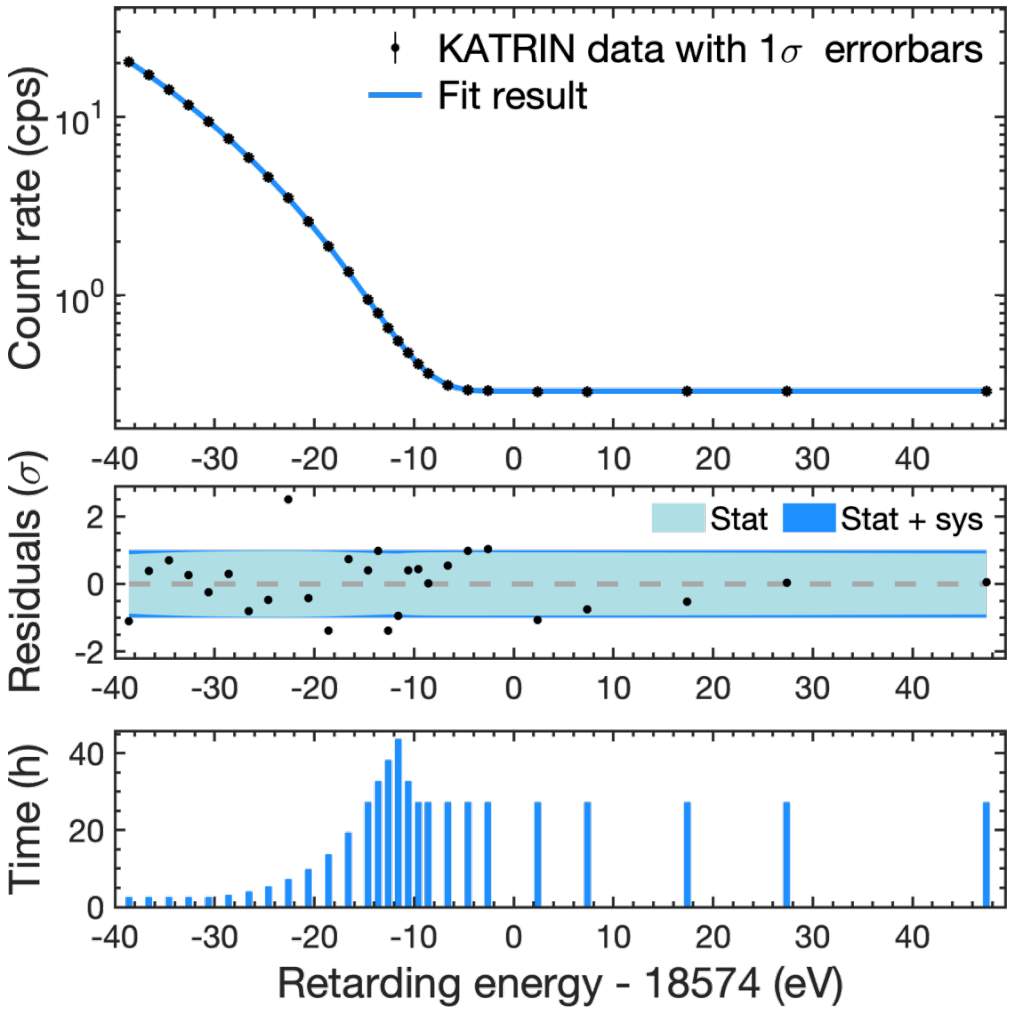
Budget of uncertainties

we are largely statistics dominated !!!



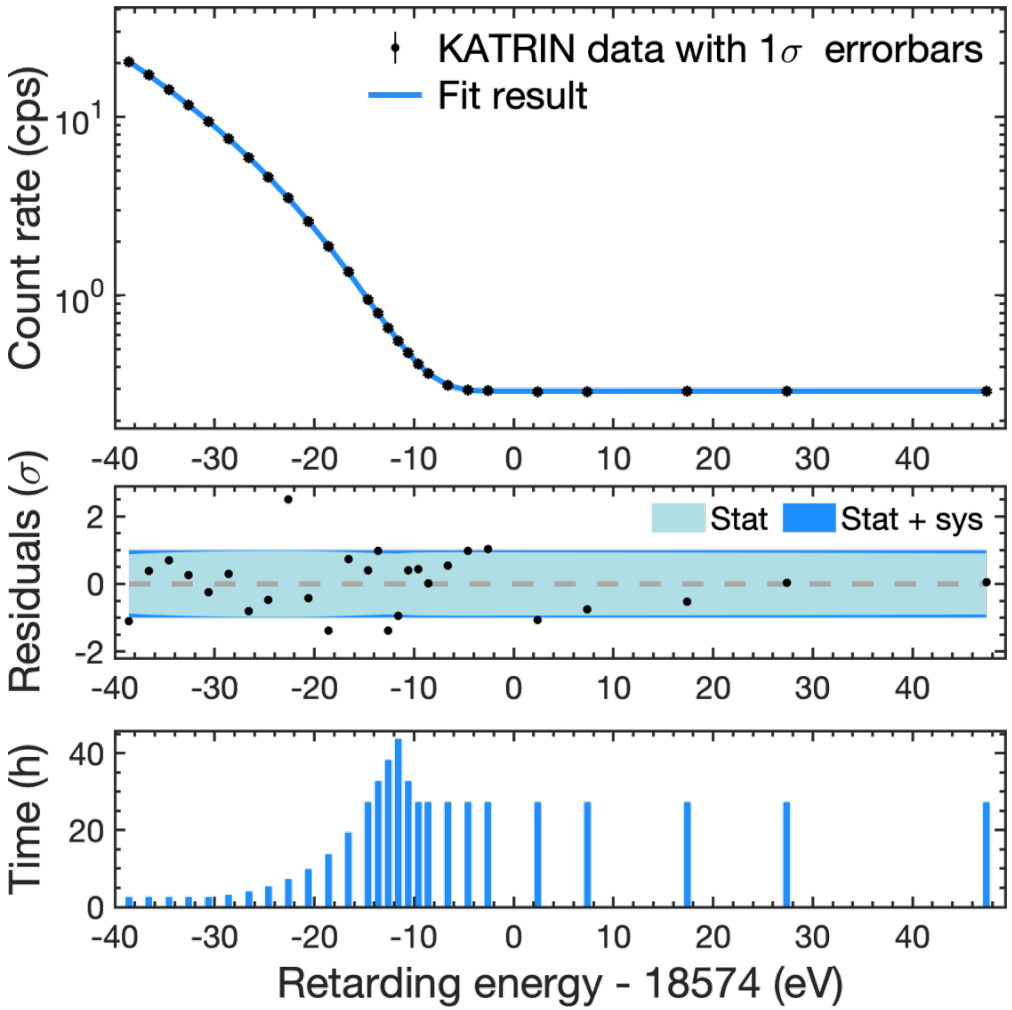
S. Goerhardt et al., JINST 13 (2018) no.10, T10004
S. Mertens et al, Astropart. Phys. 41 (2013), 52–62

Full data set



- 2 million events
- 4 free parameters:
  background, signal normalization, E_0, m_ν^2
- excellent goodness-of-fit:
  p-value = 0.56

Final fit result and upper limit



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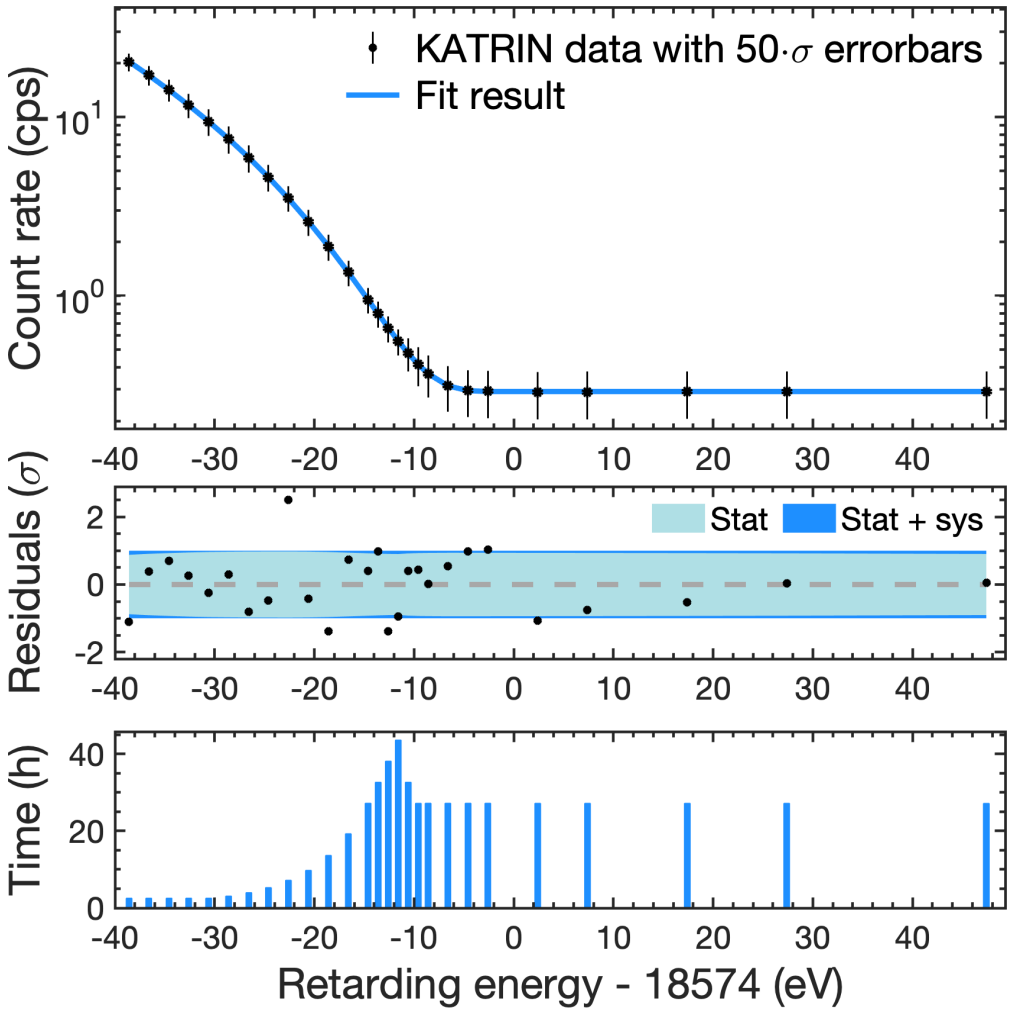
- Neutrino mass best fit:
  $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)\text{eV}^2$
- Improved upper limit:
  $m_\nu < 1.1$ eV @ 90% CL

Final fit result and upper limit



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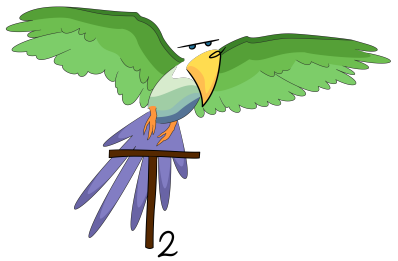
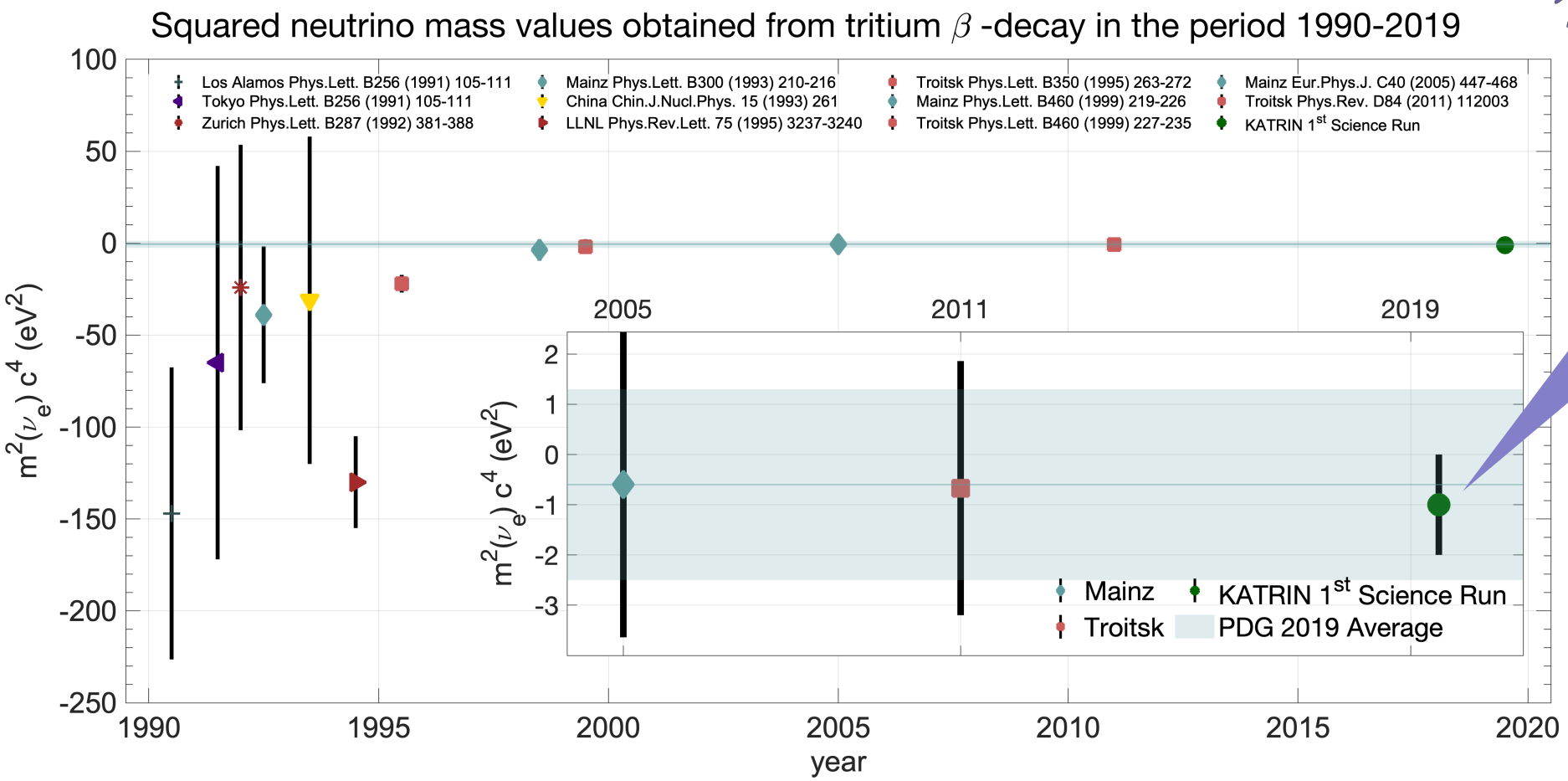
Historical context

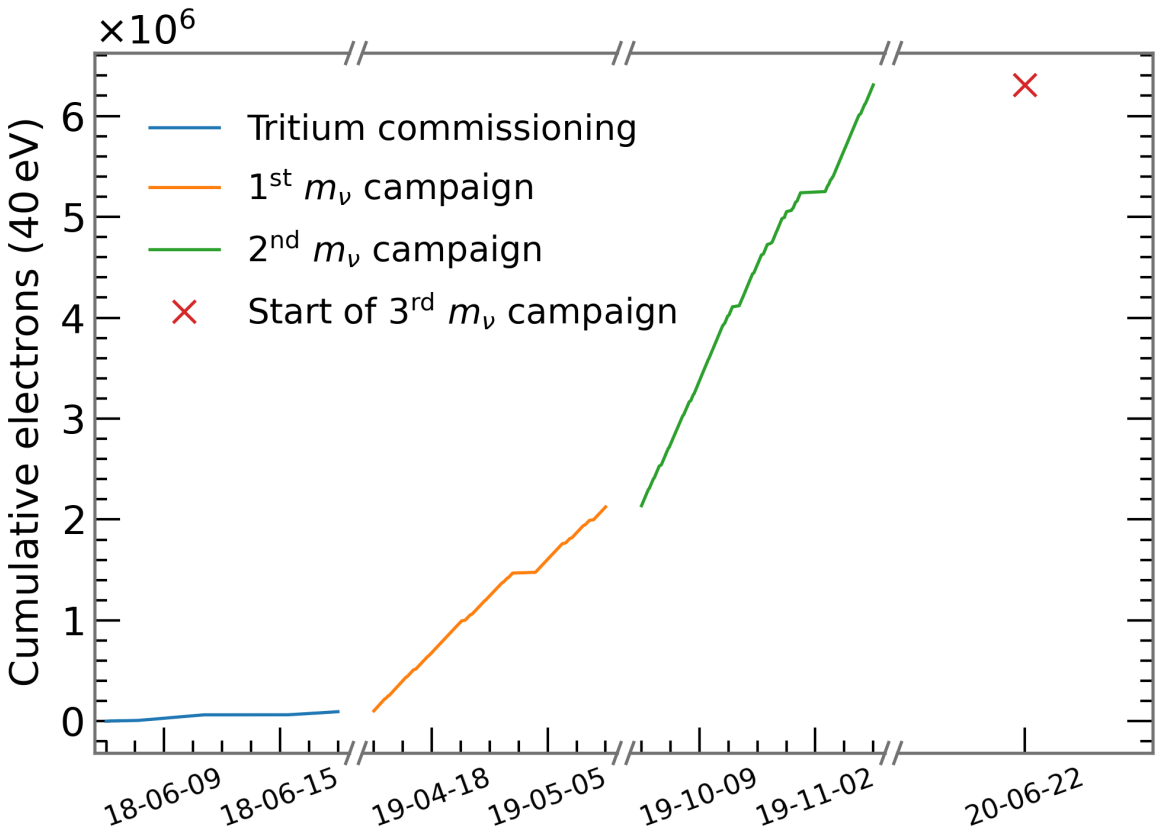




Effective 5 days of data
- Stat. error: ÷ 2
- Syst. error: ÷ 6

KATRIN Collab, Phys. Rev. Lett. 123, 221802

KATRIN - outlook

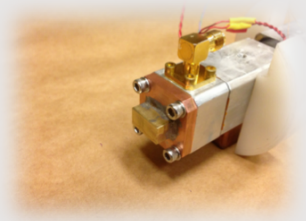


- ✓ 2nd m_ν campaign @ **full source density** completed (4 mio electron, ~0.7 eV sensitivity)
- ✓ Improved understanding of source **plasma**
- ✓ Reduced **background** level
- ✓ 3rd m_ν campaign started 2 weeks ago
- ✓ Low sub-eV sensitivity will be reached in the near future

Experimental efforts

Electrostatic filter (MAC-E)

Project-8 (Tritium)



Cyclotron Radiation

Phonons

PROJECT 8 - Experiment

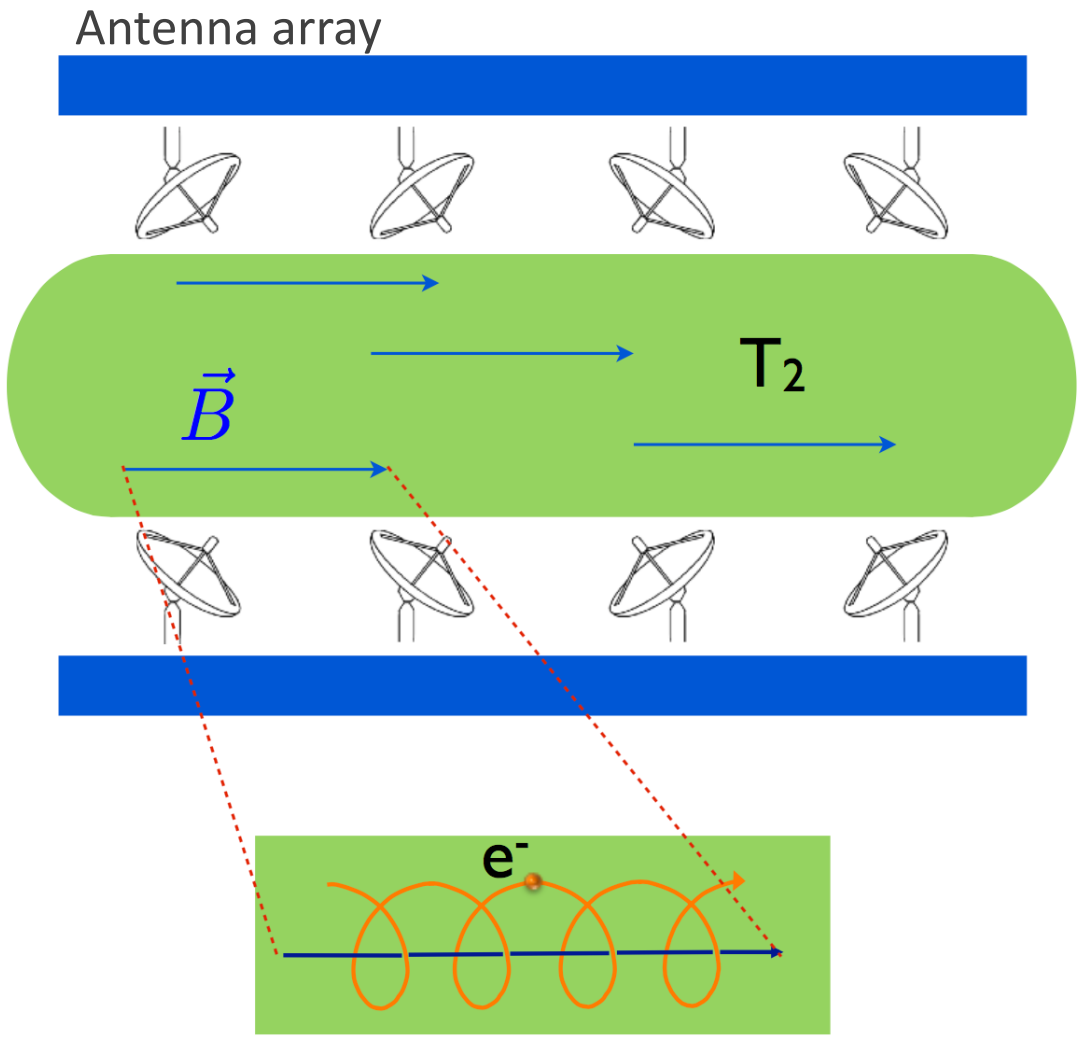
Case Western Reserve University
Harvard-Smithsonian Center for Astrophysics
Johannes Gutenberg-Universität Mainz
Karlsruher Institut für Technologie
Lawrence Livermore National Laboratory
Massachusetts Institute of Technology
Pacific Northwest National Laboratory
Pennsylvania State University
University of Washington
Yale University

Project 8 – Working principle

- Detection of cyclotron radiation with antenna array

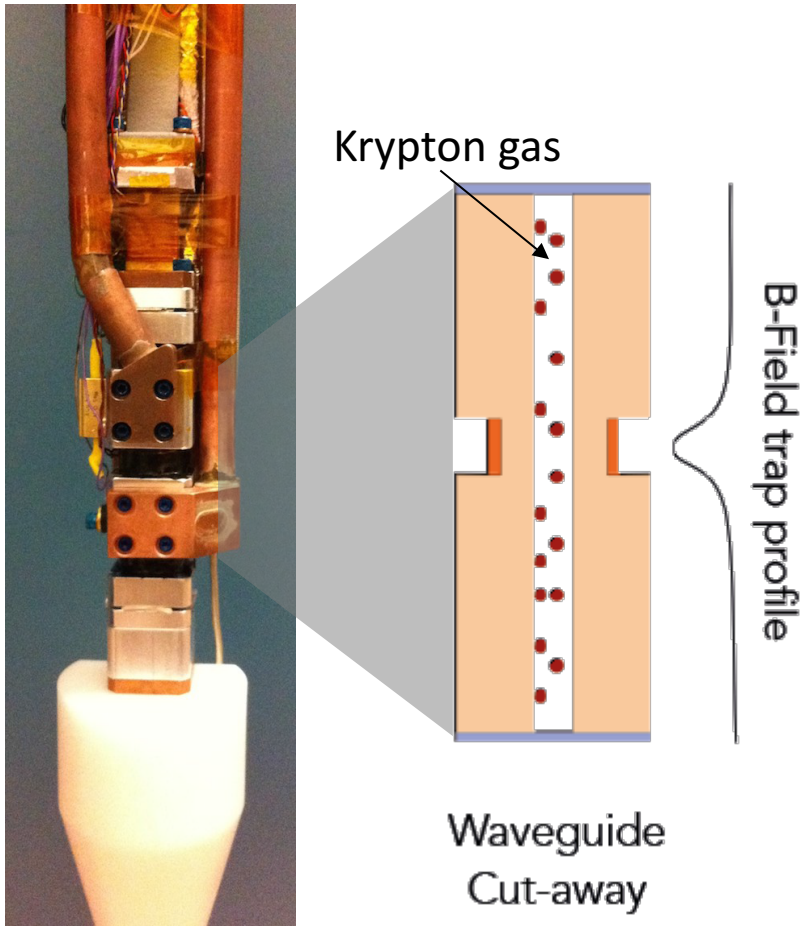
- Cyclotron Radiation Emission Spectroscopy (CRES)

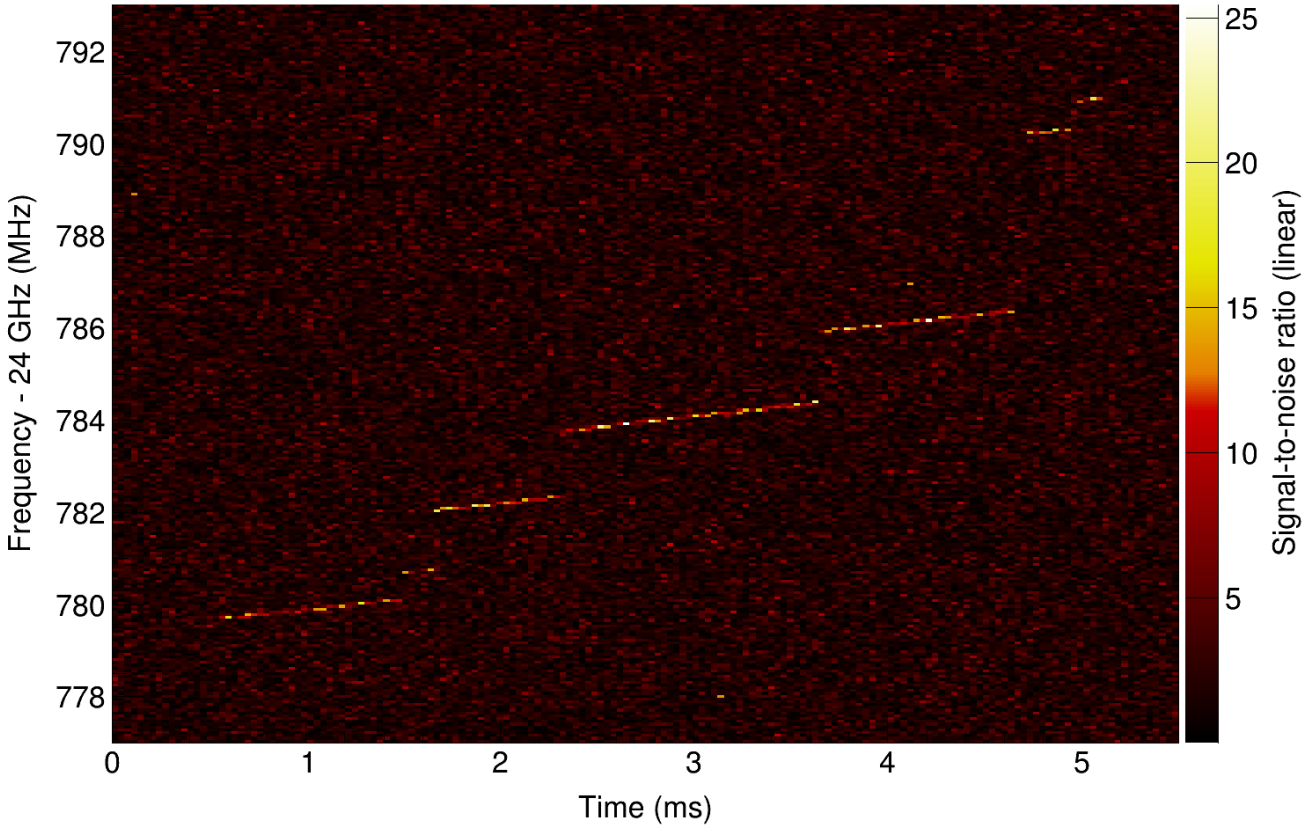
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{E + m_e}$$



B. Monreal and Joe Formaggio, Phys. Rev D 80:051301

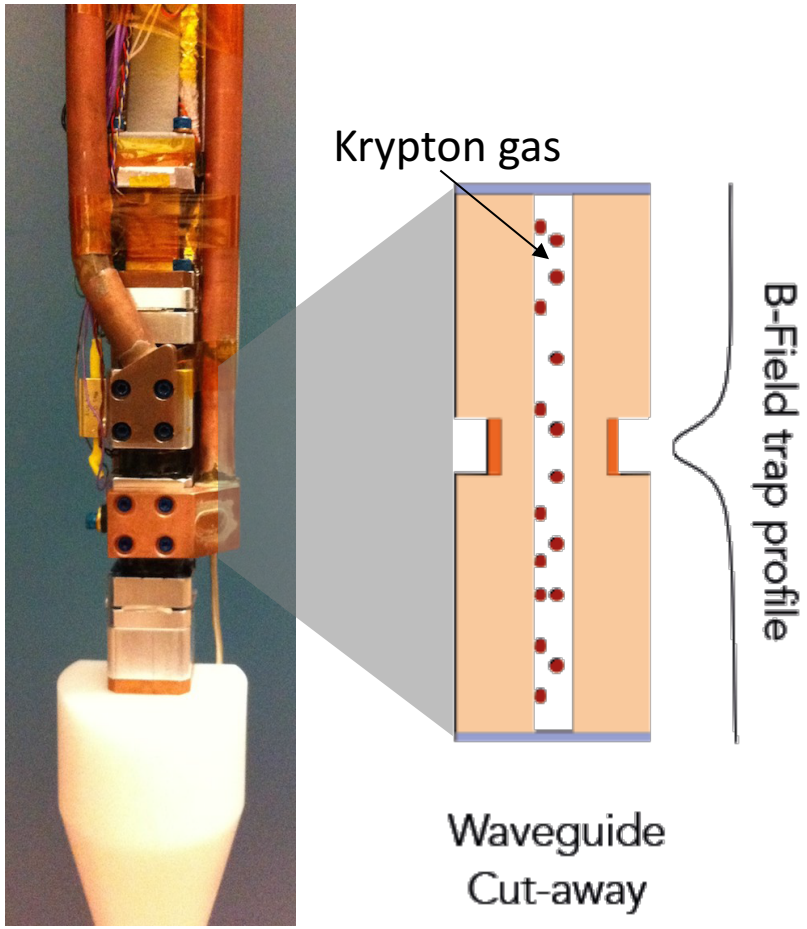
Project 8 – Phase 1: *proof of concept*

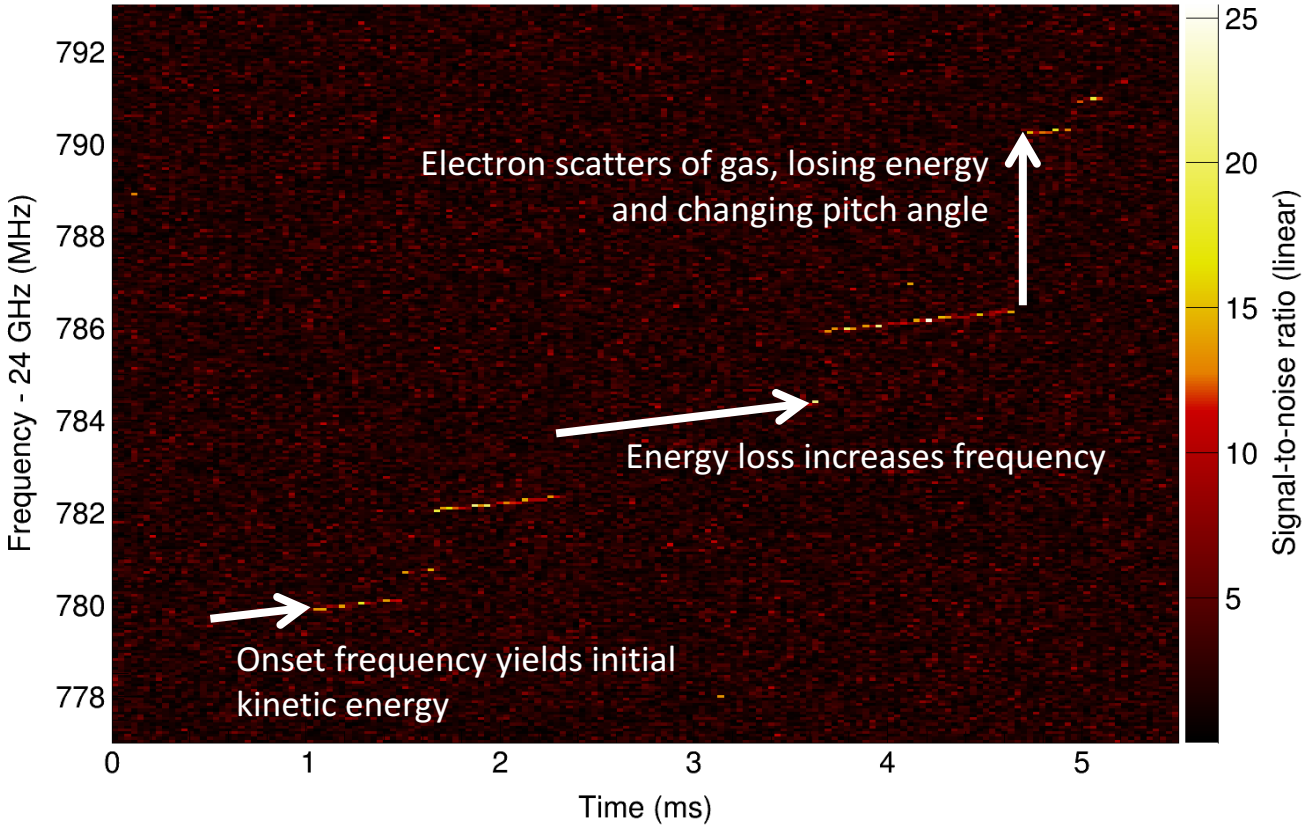




D.M. Asner et al., Phys. Rev. Lett. 114, 162501 (2015)

Project 8 – Phase 1: *proof of concept*

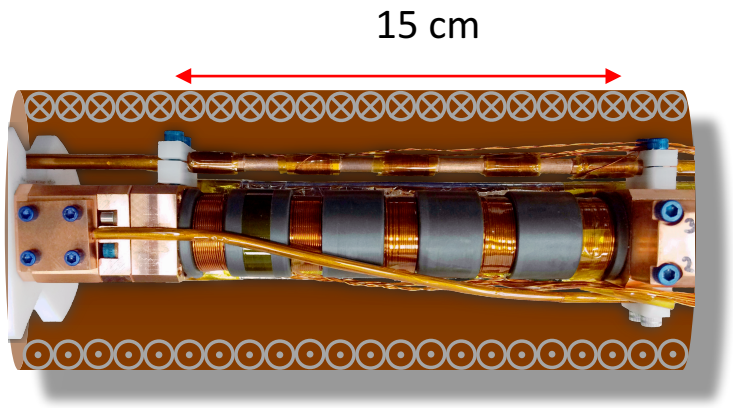


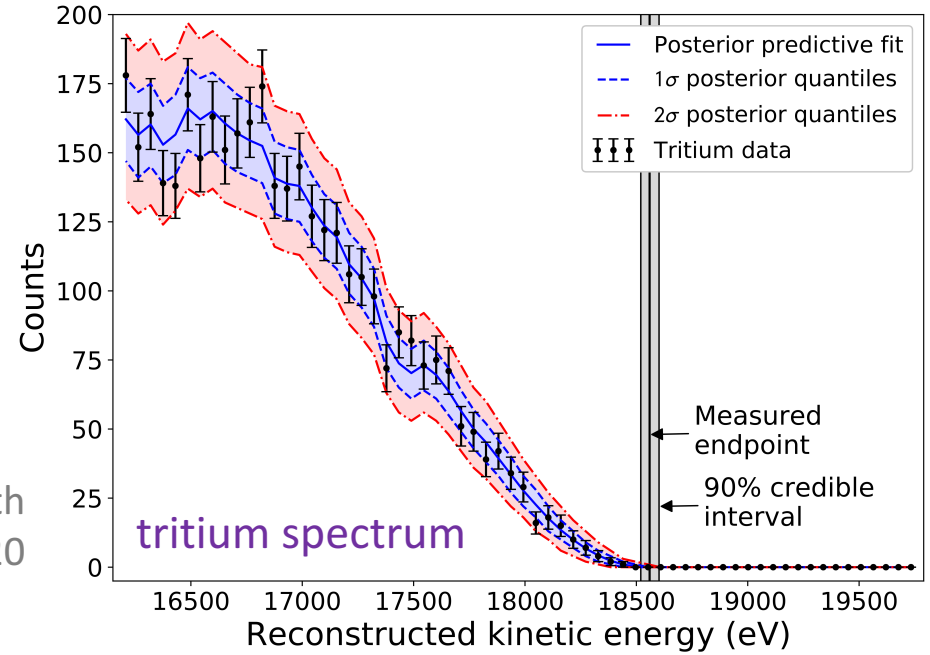


D.M. Asner et al., Phys. Rev. Lett. 114, 162501 (2015)

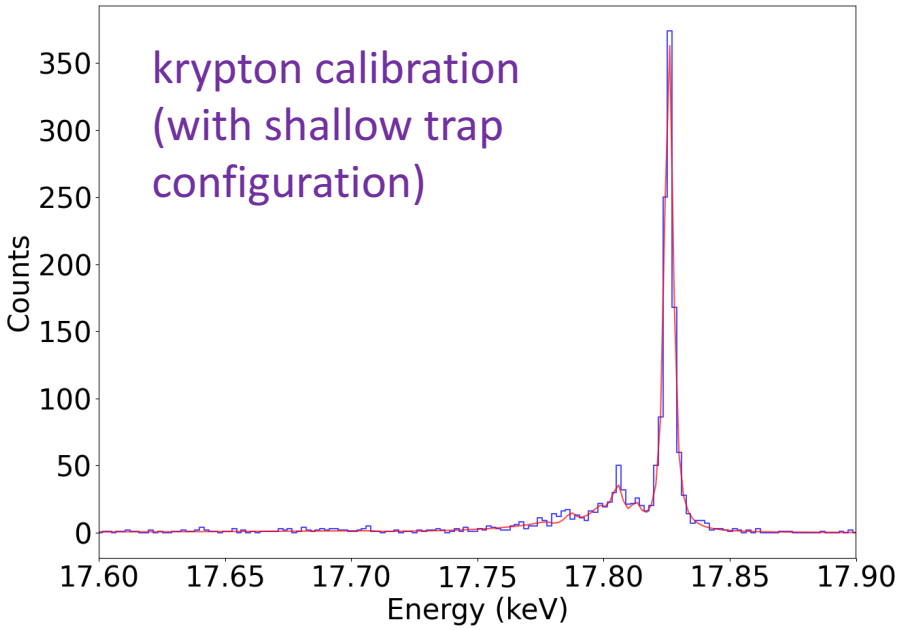
Project 8 – Phase 2: *tritium*

- ✓ Energy resolution: 2.0 ± 0.1 eV (FWHM)
- ✓ Energy linearity: < 50 meV (ppm-level)
- ✓ Tritium endpoint measurement: $E_0 = 18559.4^{+24.9}_{-24.7}$ eV
- ✓ Background estimation: $\leq 3\times10^{-10}$ eV^{-1} s^{-1}





see talk of Noah Oblath at Neutrino-2020



PROJECT 8

Project 8 – Phase 3 and 4

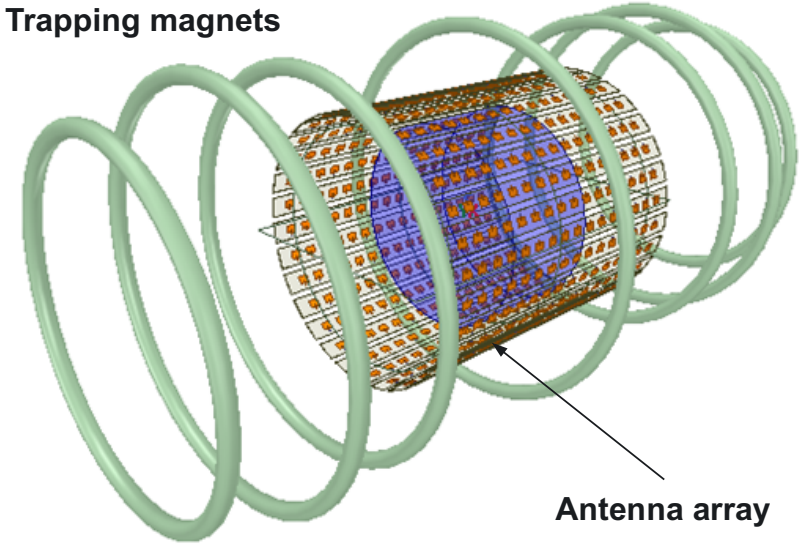
Phase – 3

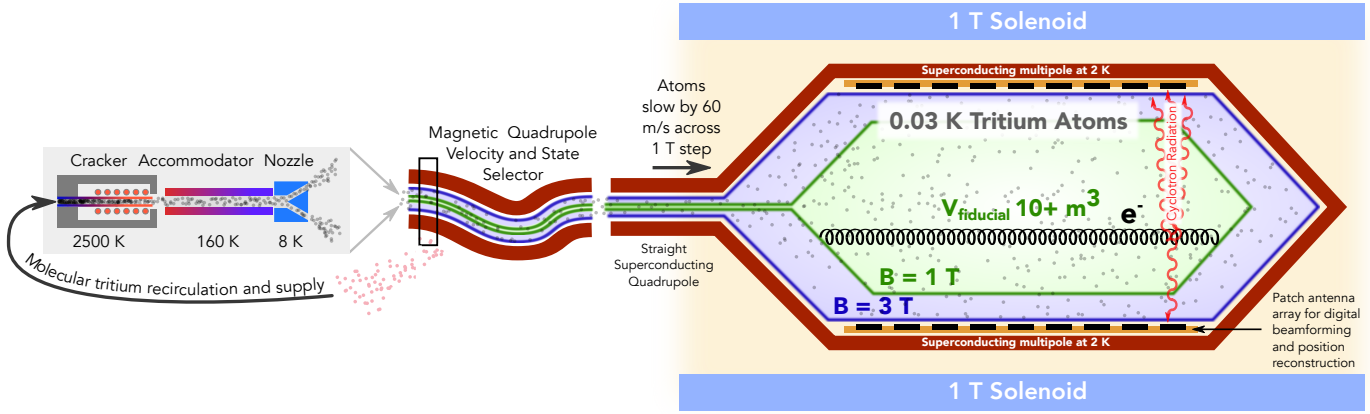
✓ Large volume trap: 200 cm^3 inside an MRI magnet
→ goal $m_\nu < 2$ eV

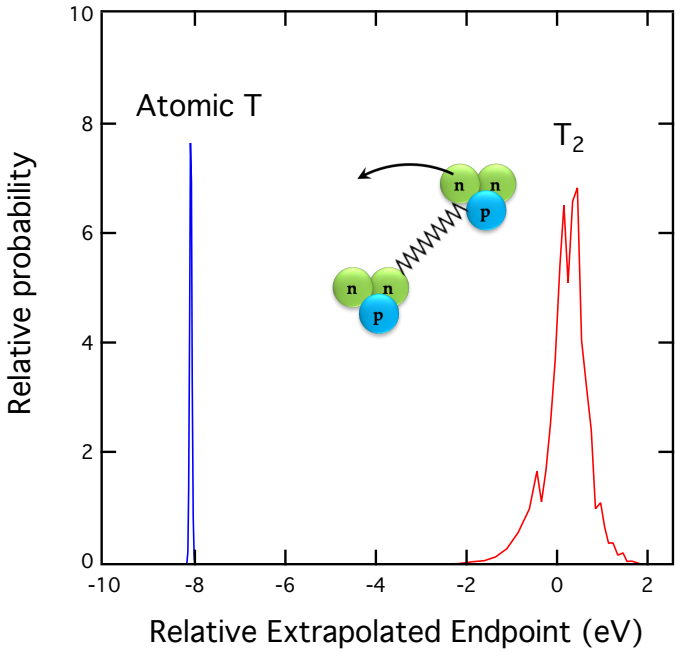
✓ Demonstration of **atomic tritium** source

Phase – 4

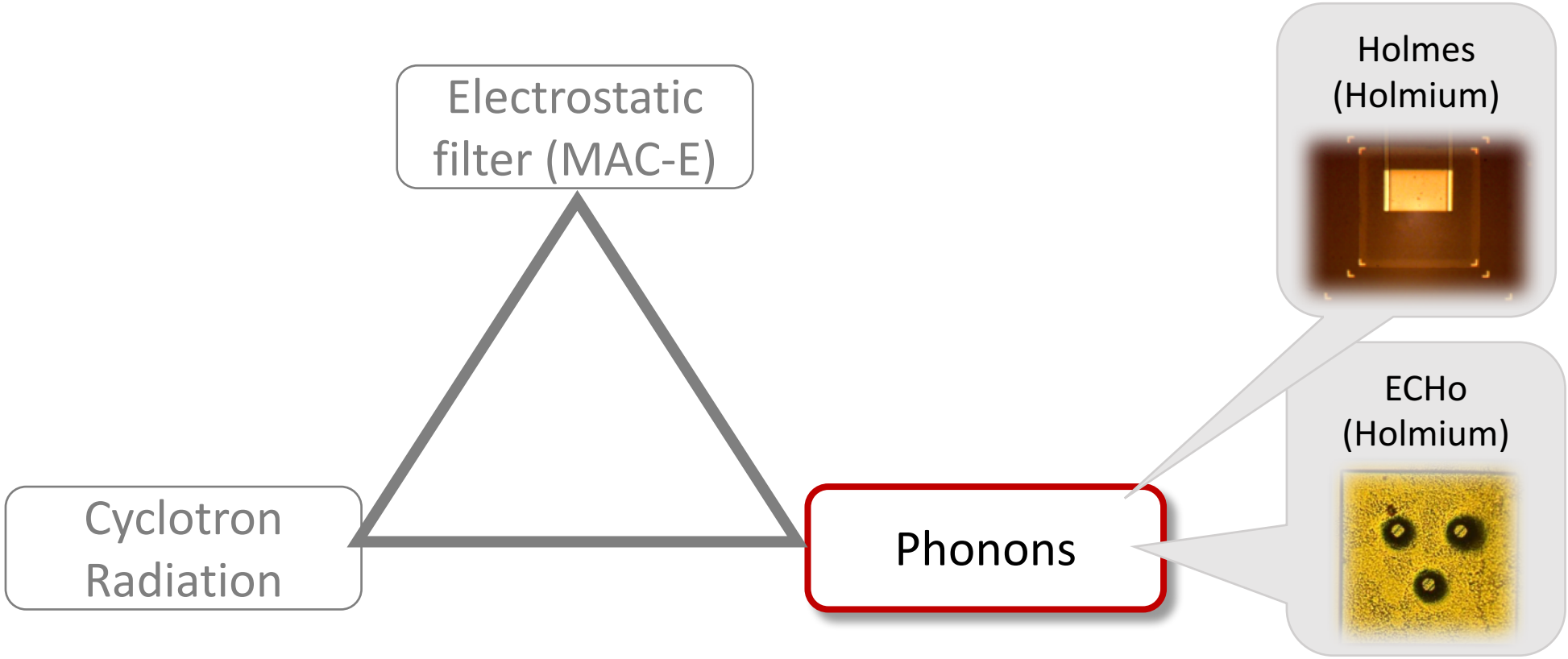
✓ $m_\nu < 40$ meV final sensitivity





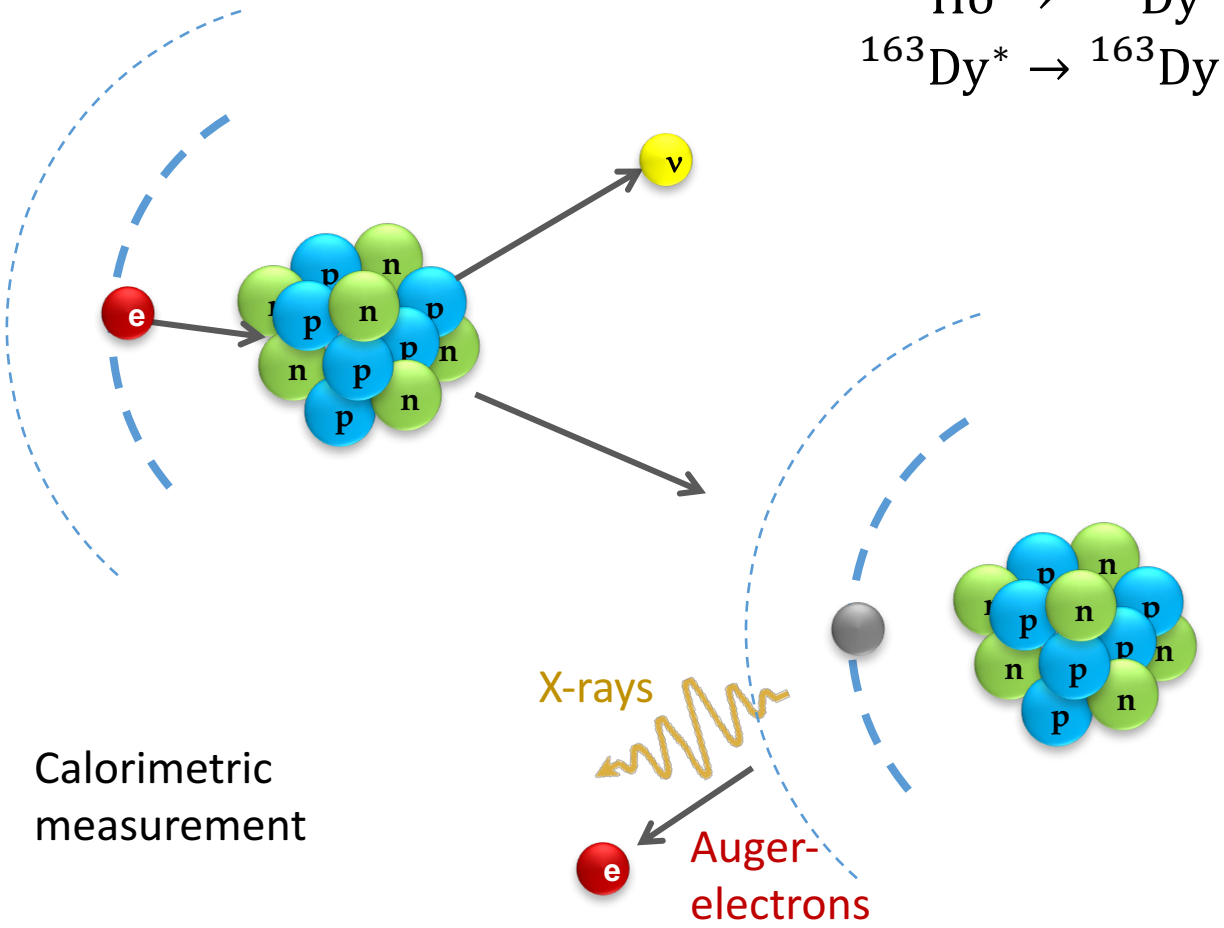


Experimental efforts



Basic Idea

$$^{163}\mathrm{Ho} \rightarrow {}^{163}\mathrm{Dy}^{*} + \nu_e$$
$$^{163}\mathrm{Dy}^{*} \rightarrow {}^{163}\mathrm{Dy} + E_C$$



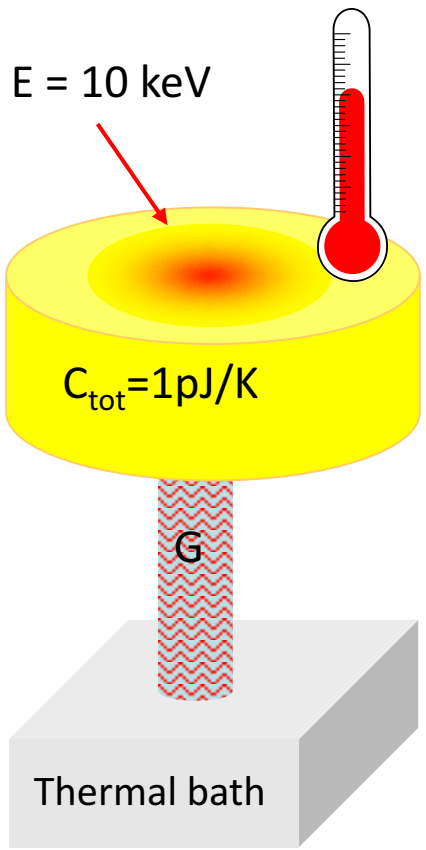
Atomic de-excitation energy

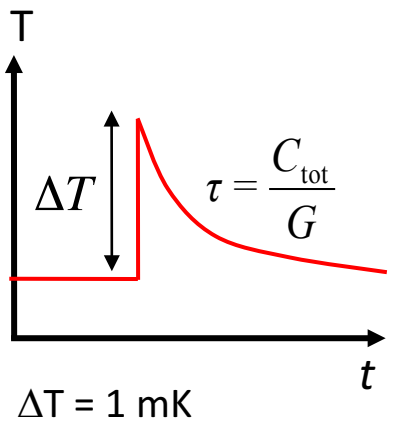
- X-ray emission
- Auger electrons

Calorimetric measurement

A. De Rujula et at., Phys. Lett. B 118 (4-6) (1982)

Calorimetric measurement





Advantage:

- Source = Detector
- All energy is detected

Challenge (for < 1-eV sensitivity)**:**

- Handle > 1 Mcps total rate

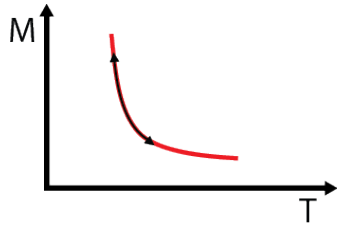
➢ Fast signals: $\tau < 1\ \mu s$

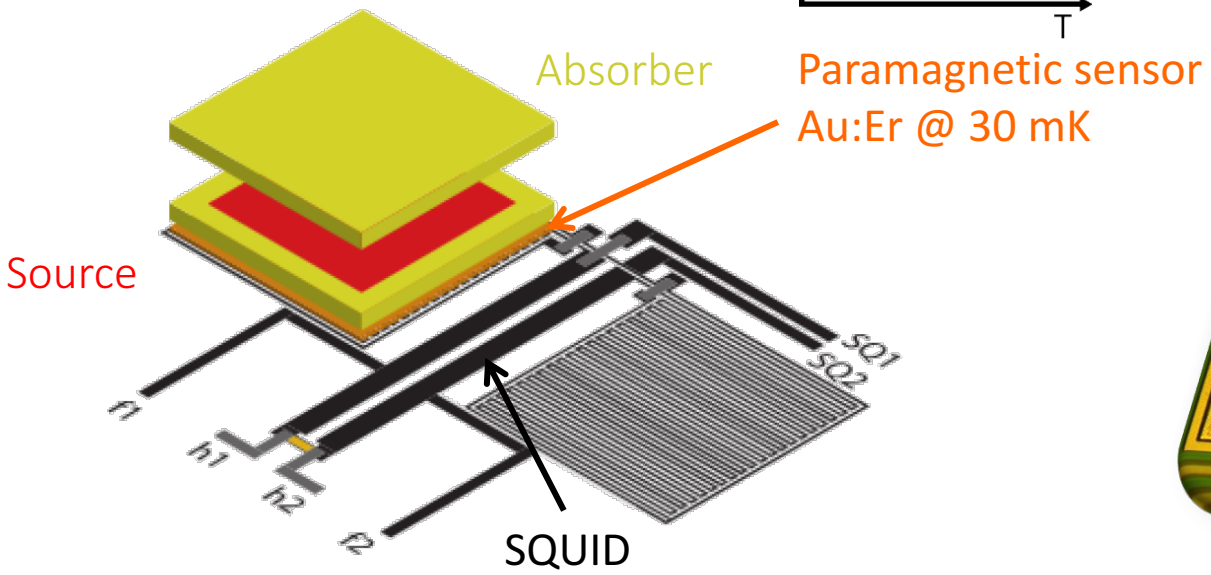
➢ Large number of detectors: > 10^5

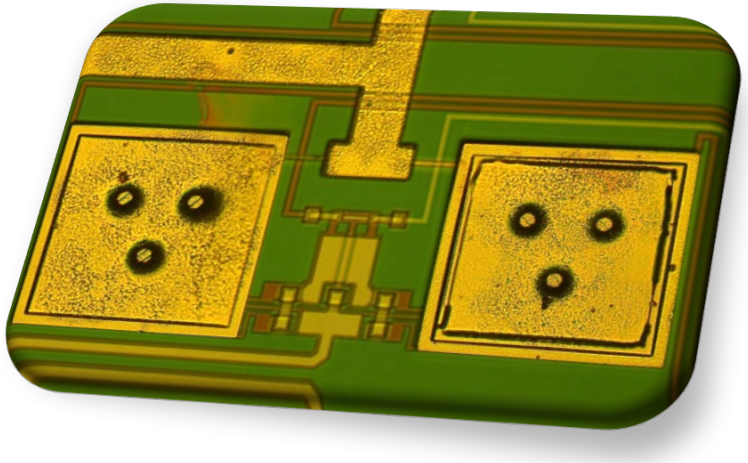
Experiments

ECHo	HOLMES
U. Heidelberg, MPIK Heidelberg, U. Bratislava, U. Frankfurt, U. Mainz, TU Dresden, Humboldt U. Berlin, U. Tübingen, Institute Laue-Langevin in Grenoble, ISOLDE-CERN, Nuclear Physics Institute in Russia	U. Milano-Bicocca, INFN Sez. Milano-Bicocca, INFN Sez. Genova, INFN Sez. Roma, Institute Laue-Langevin in Grenoble, U. Lisboa, U. Miami, NIST in Boulder, JPL in Pasadena, PSI in Villingen

ECHo



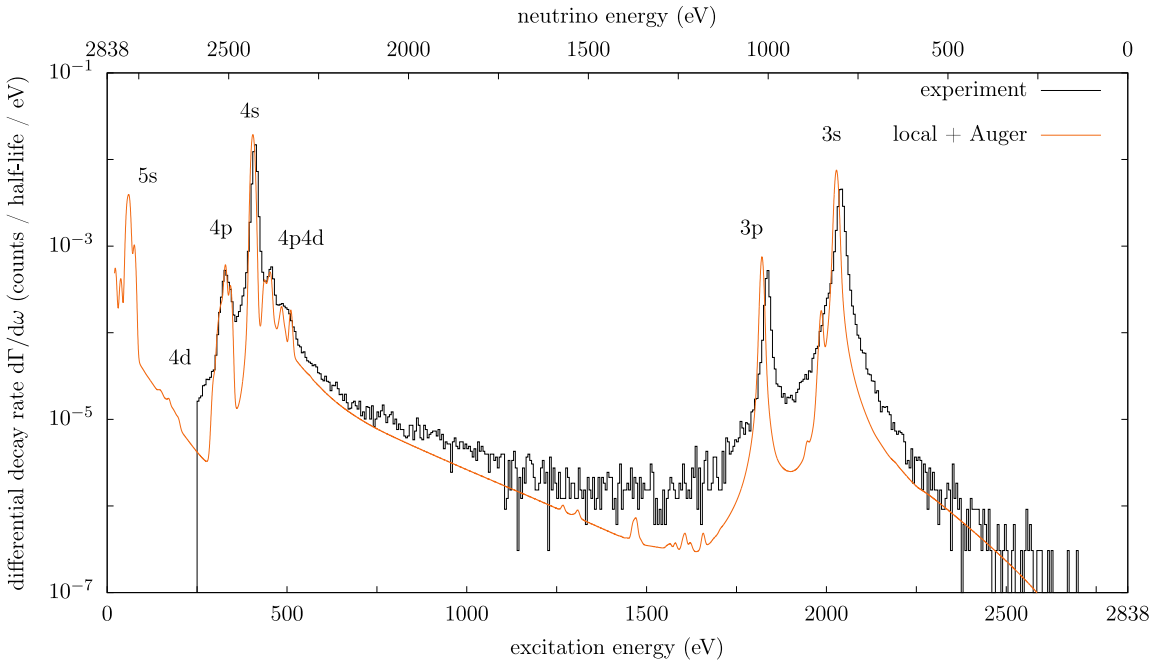


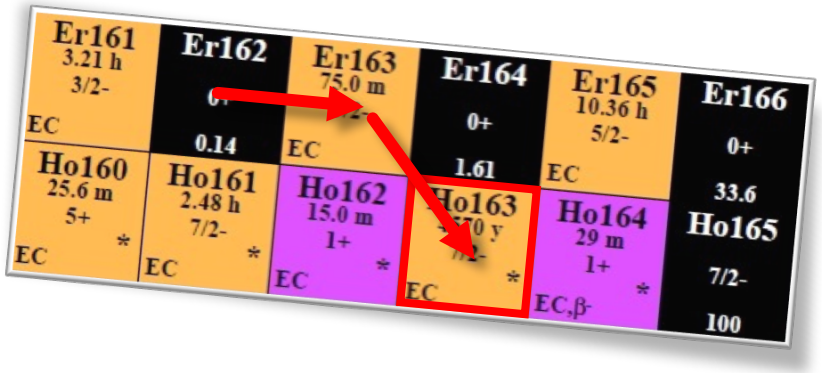


- low temperature metallic magnetic calorimeters (MMC) with enclosed ^{163}Ho
  A. Fleischmann et al., *AIP Conf. Proc.* **1185**, 571, (2009)
  L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)
- measure temperature change via change of magnetization of sensor
- operated at 20 mK

ECHo

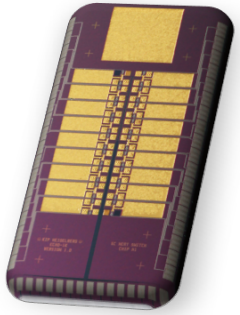
- ✓ excellent detector performance:
  - ✓ energy resolution (5 eV @ 6 keV)
  - ✓ fast rise time (130 ns)
  - ✓ low background (~10^{-4} events/eV/pixel/day)
  - ✓ multiplexed readout
- ✓ first holmium spectra measured
  Phys. Rev. Lett. ***119****, 122501 (2017)*
- ✓ refined calculation of the holmium spectrum
  M. Braß, Phys.Rev.C 97 (2018), arXiv:2002.05989 [nucl-th] (2020)
- ✓ first limit on the neutrino mass: $m(\nu_e) < 150$ eV (95% C.L.)
  C. Velte et al., Eur. Phys. J. C 79 (2019) 1026





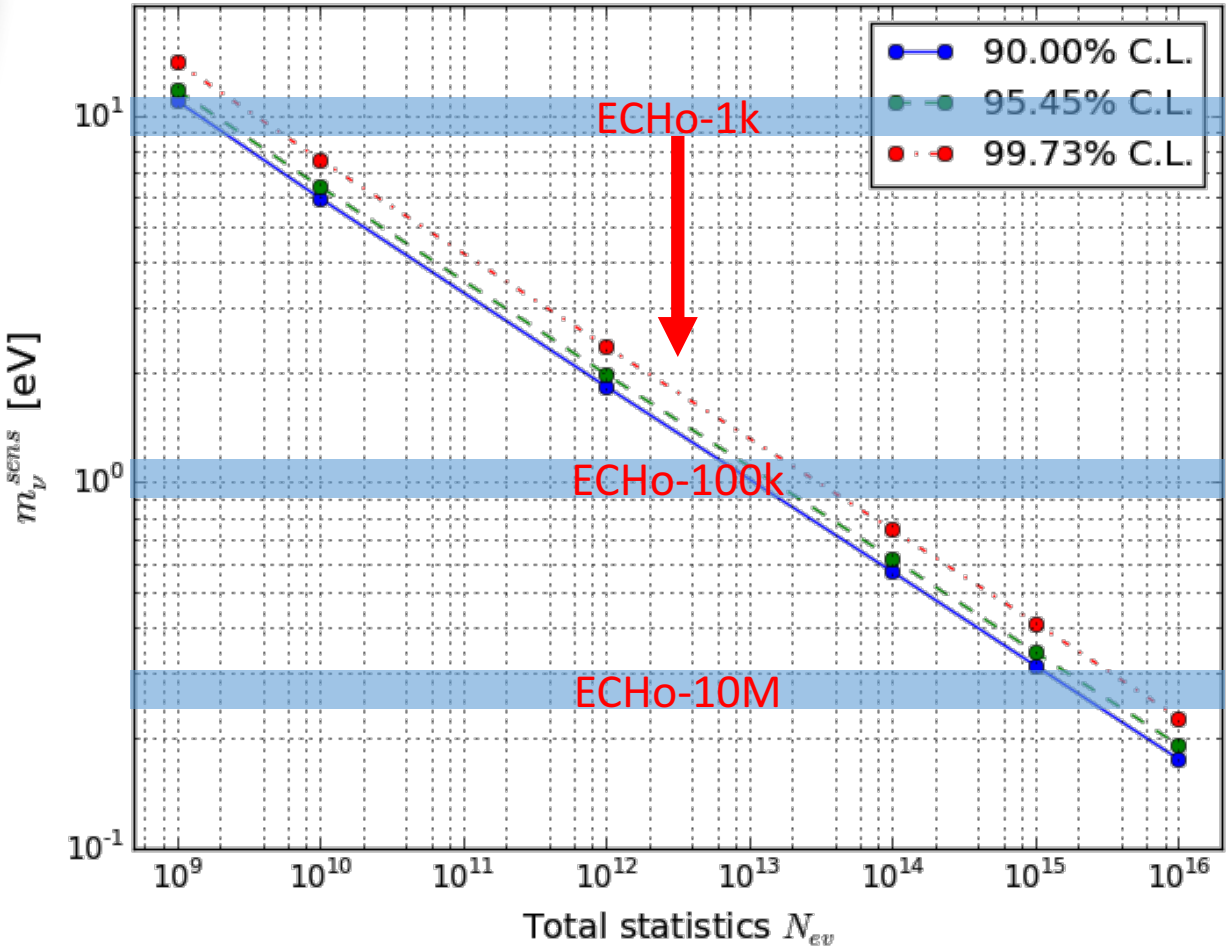
ECHo - Schedule

- **ECHo-1k** (running, finished 2020)
  - ~1 Bq/pixel, ~100 detectors
  - goal: 20 eV sensitivity



- **ECHo-100k** (in preparation, start 2021)
  - 10 Bq/pixel 12,000 detectors
  - goal: 1 eV sensitivity (3 years)

- **ECHo-10-MBq**:
  - total statistics of 10^{15} - 10^{16} decays
  - goal: low sub-eV sensitivity

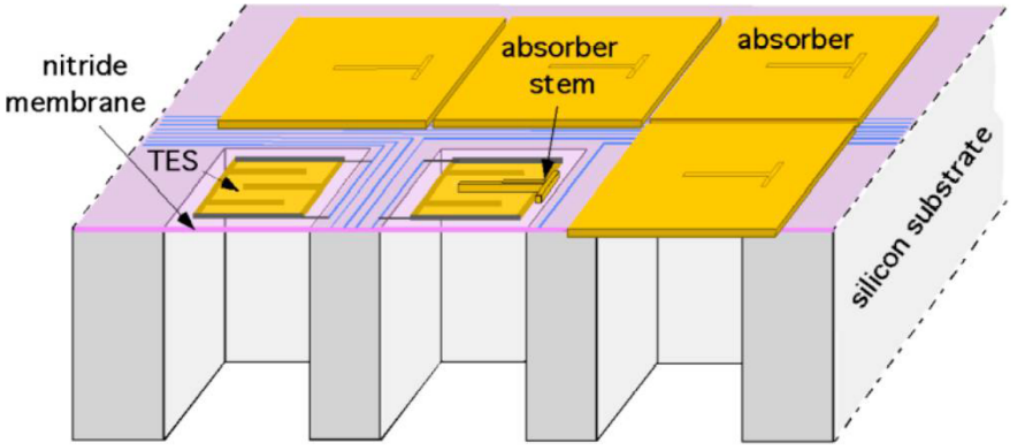


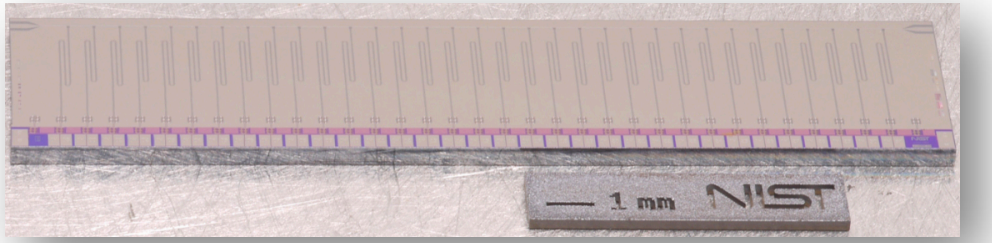
HOLMES

J Low Temp Phys **184,** 922–929 (2016)

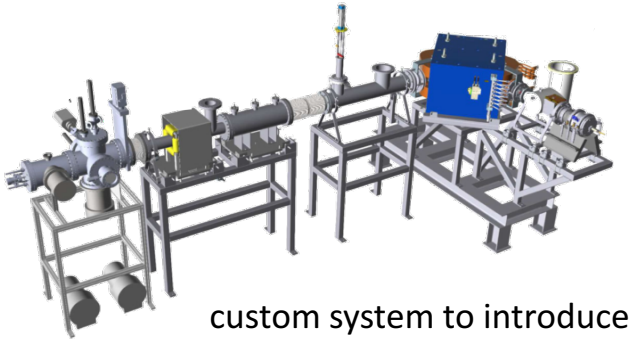
Key features:

- ✓ transition edge sensors (TES) – NIST
  J Low Temp Phys **184,** 492–497 (2016)
- ✓ microwave multiplexing (µMUX) – NIST
  JINST 14 (2019) P10035
- ✓ successful test of integrated detector and read-out system in cryostat
  - ✓ energy resolution (4.5 eV (FWHM) @ 6 keV)
  - ✓ fast rise time (+ efficient pile-up detection)
  - ✓ low background (~10^{-4} events/eV/pixel/day)





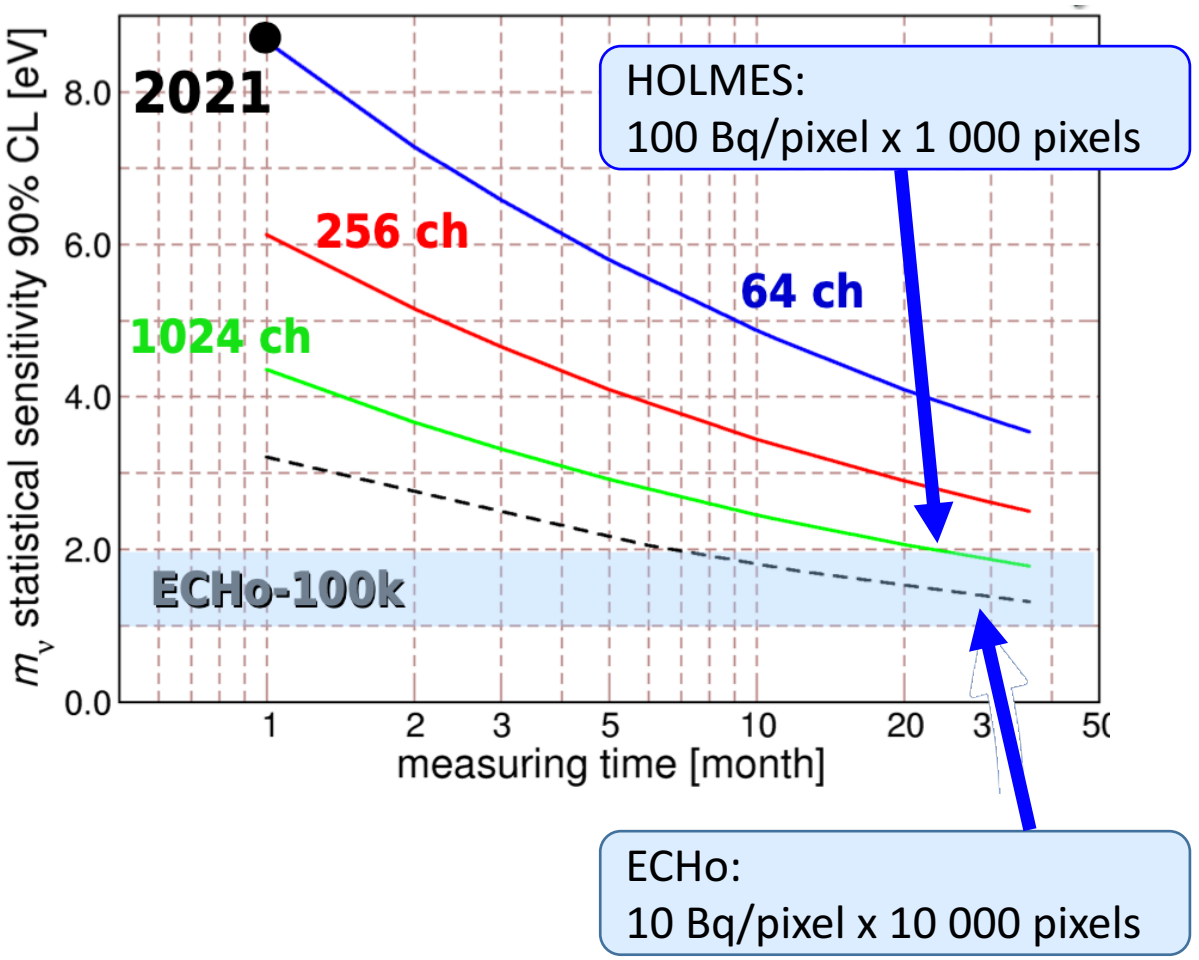
HOLMES



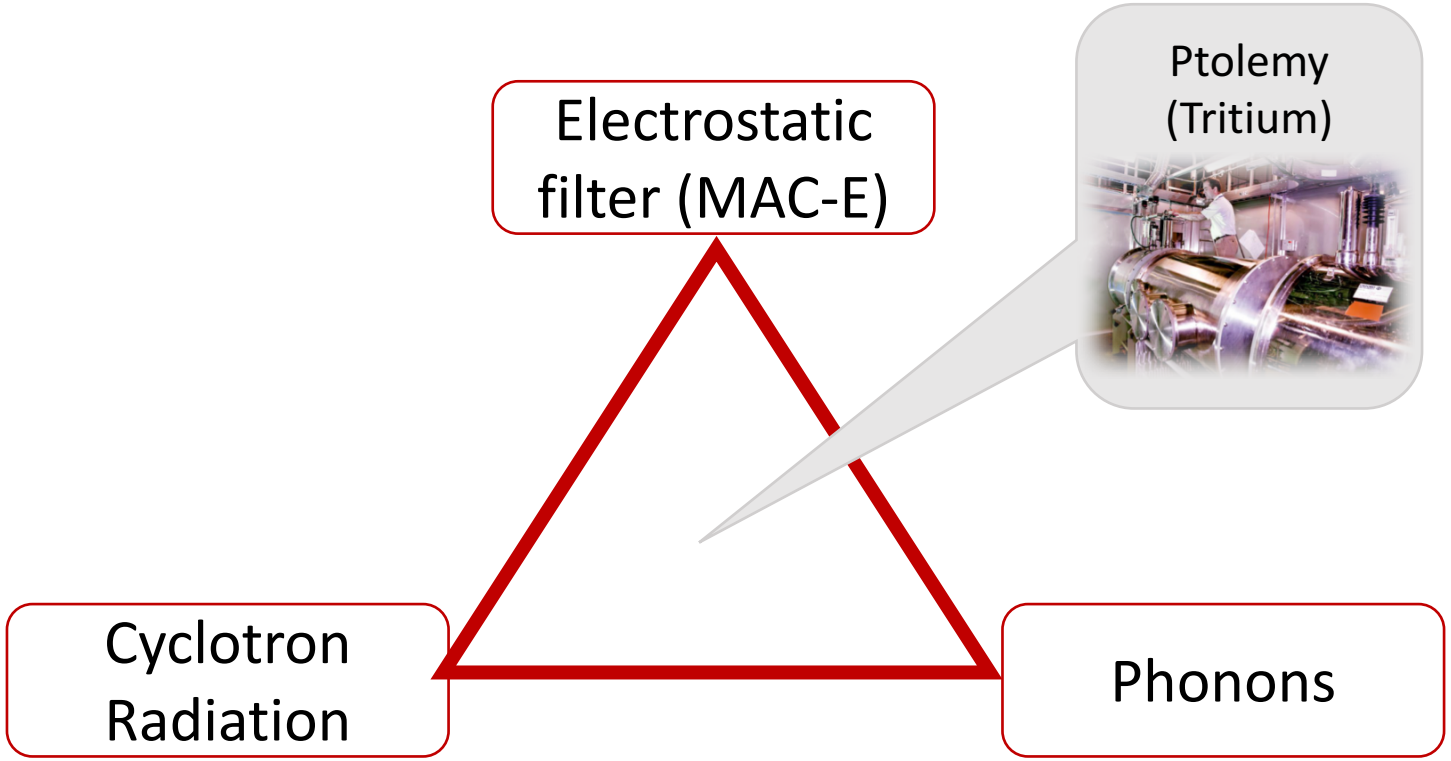
custom system to introduce Ho in absorber

Approach:

- high activity (300 Bq) per pixel
  - less detectors ☺
  - less stringent background requirement ☺
  - need advanced pile-up rejection algorithms ☹
- optimization for high-dose ^{163}Ho implantation
- 1-eV sensitivity to be reached in a few years (~100 Bq/pixel and 1000 pixels)
- compare HOLMES vs. ECHo approach to find optimal path to the low sub-eV sensitivity



Experimental efforts



Very interesting ideas to combine the best of all technologies

Sensitivity to < 10 meV

Summary

KATRIN

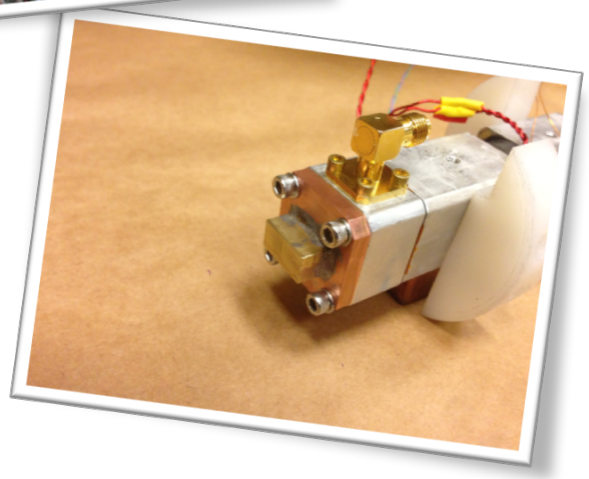
- World-leading limit on neutrino mass from direct measurements
- Improved **plasma** understanding, reduced **background**
- Low sub-eV limit (0.2 eV) to be reached in about ~5 years

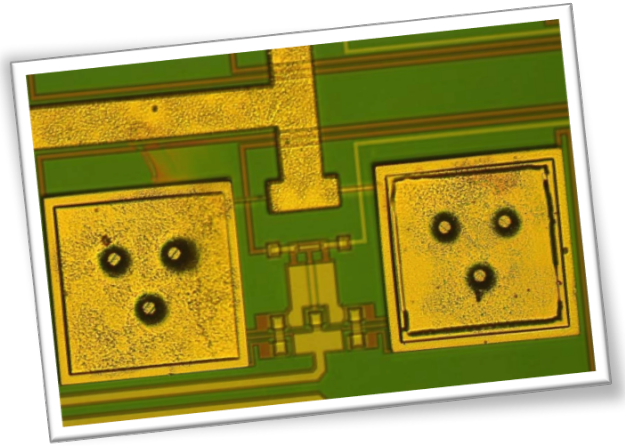
Project 8

- Proved a completely new concept via frequency measurement
- Successful first tritium measurements
- Sub-eV challenge: **large-scale volume trap**

ECHo & Holmes

- Demonstrated excellent performance of micro-calorimeters
- Successful first holmium measurements and improved theoretical calculations
- Sub-eV challenge: Scaling-up to **high-activity** and **large number of detectors**





Thank you for your attention

Thanks to the KATRIN collaboration
Noah Oblath
Angelo Enrico Nucciotti
Lorenda Gastaldo

Dr. Susanne Mertens

Technical University Munich & Max Planck Institute for Physics